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Chang et al.

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(54) **HIGH-THROUGHPUT, LOW-LATENCY
NEXT GENERATION INTERNET
NETWORKS USING OPTICAL LABEL
SWITCHING AND HIGH-SPEED OPTICAL
HEADER GENERATION, DETECTION AND
REINSERTION**

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patent is extended or adjusted under 35
U.S.C. 154(b) by 0 days.

This patent is subject to a terminal dis-
claimer.

(21) Appl. No.: **09/353,228**

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Jul. 17, 1998, now Pat. No. 6,111,673.

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1998.

(51) Int. Cl.⁷ **H04J 14/02**

(52) U.S. Cl. **359/124; 359/123; 359/128;
370/471**

(58) Field of Search **359/123-124,
359/128, 135; 370/352, 355-356, 392, 471**

(56) **References Cited**

U.S. PATENT DOCUMENTS

4,797,879 A	1/1989	Habbab et al.	359/123
4,831,616 A	5/1989	Huber	359/137
5,018,130 A	5/1991	Suzuki et al.	359/124
5,101,290 A	3/1992	Eng et al.	359/123
5,337,185 A	8/1994	Meier et al.	359/321
5,488,501 A	1/1996	Barnsley	359/137

5,550,818 A	8/1996	Brackett et al.	370/395.51
5,589,967 A	12/1996	Auffret	359/123
5,623,356 A	4/1997	Kaminow et al.	359/123
5,706,375 A	1/1998	Mihailov et al.	385/24
5,734,486 A	3/1998	Guillemot et al.	359/139
5,745,612 A	4/1998	Wang et al.	385/24
5,838,848 A	11/1998	Laude	385/24
5,912,753 A	6/1999	Cotter et al.	359/137

(List continued on next page.)

FOREIGN PATENT DOCUMENTS

EP	0702479	3/1996
EP	0949837	10/1999
WO	WO 00/44118	1/2000
WO	WO 01/35185	10/2000

OTHER PUBLICATIONS

Wagner, R.E. et al.; "MONET: Multi-Wavelength Optical
Networking," Journal of Lightwave Technology, vol. 14,
No. 6, pp. 1349-1355, Jun., 1996.

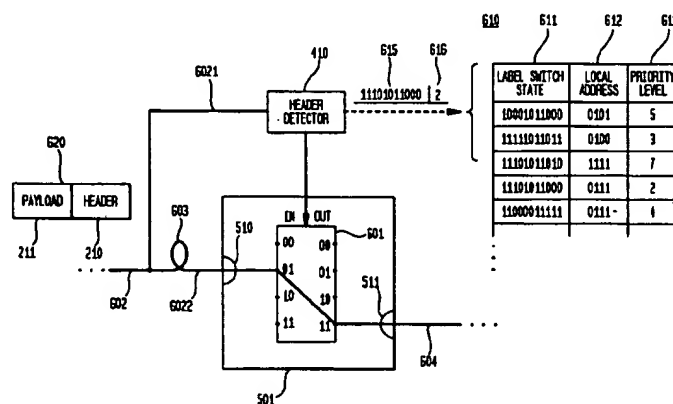
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Primary Examiner—Kinfe-Michael Negash

(57) **ABSTRACT**

An optical signaling header technique applicable to optical
networks wherein packet routing information is embedded
in the same channel or wavelength as the data payload so
that both the header and data payload propagate through
network elements with the same path and the associated
delays. The header routing information has sufficiently dif-
ferent characteristics from the data payload so that the
signaling header can be detected without being affected by
the data payload, and that the signaling header can also be
removed without affecting the data payload. The signal
routing technique can overlaid onto the conventional net-
work elements in a modular manner using two types of
applique modules. The first type effects header encoding and
decoding at the entry and exit points of the data payload into
and out of the network; the second type effects header
detection at each of the network elements.

38 Claims, 14 Drawing Sheets



U.S. PATENT DOCUMENTS

5,920,663	A	7/1999	Dragone	385/15
5,978,119	A	11/1999	Giles et al.	359/132
5,995,256	A	11/1999	Fee	359/124
6,023,544	A	2/2000	Dragone	385/24
6,108,113	A	8/2000	Fee	359/124
6,111,673	A	8/2000	Chang et al.	359/123
6,160,651	A	12/2000	Chang et al.	359/124
6,271,946	B1	8/2001	Chang et al.	359/124

OTHER PUBLICATIONS

Chang et al.; "Multiwavelength Reconfigurable WDM/ATM/SONET Network Testbed," *Journal of Lightwave Technology*, vol. 14, No. 6, pp. 1320-1340, Jun., 1996.

Kaminow, IP. et al.; "A Wideband All-Optical WDM Network," *IEEE Journal on Selected Areas of Communications*, vol. 14, No. 5, pp. 780-799, Jun., 1996.

Maxemchuk, N.F.; "The Manhattan Street Network," *Proceedings on IEEE Globecom '85*, pp. 255-261, Dec., 1985.

Budman, A. et al.; "Multigigabit Optical Packet Switch for Self-Routing Networks with Subcarrier Addressing," *Technical Digest, Paper TuO4*, pp. 90-91, OFC, 1992.

Way, W.I. et al.; "Self-Routing WDM High-Capacity Sonet Ring Network," *Technical Digest, Paper TuO2*, pp. 86-87, OFC, 1992.

Hofmeister, R.T. et al.; "Cord: Optical Packet-Switched Network Testbed," *Fiber and Integrated Optics*, vol. 16, pp. 199-219, 1997.

Park, E. et al.; "Self-Routing of Wavelength Packets Using an All Optical Wavelength Shifter and QPSK Subcarrier Routing Control," *IEEE Photonics Technology Letters*, vol. 8, pp. 936-940, Jul., 1996.

Shell, M. et al.; "Experimental Demonstration of an All-Optical Routing Node for Multihop Wavelength Routed Networks," *IEEE Photonics Technology Letters*, vol. 8, pp. 1391-1393, 1996.

Wang, B.H. et al.; "Demonstration of Gigabit WDMA Networks Using Parallel-Processed Sub-Carrier Hopping Pilot-Tone (P3) Signaling Technique," *IEEE Photonics Technology Letters*, vol. 8, pp. 933-934, Jul., 1996.

Shieh, W. et al.; "A Wavelength-Routing Node Using Multifunctional Semiconductor Optical Amplifiers and Multiple-Pilot-Tone-Coded Subcarrier Control Headers," *IEEE Photonics Technology Letters*, vol. 9, pp. 1268-1270, Sep., 1997.

Jiang, X. et al.; "All Optical Wavelength Independent Packet Header Replacement Using a Long CW Region Generated Directly From the Packet Flag," *IEEE Photonics Technology Letters*, vol. 9, pp. 1638-1640, Nov., 1998.

Blumenthal, D.J. et al.; "WDM Optical Tag Switching with Packet-Rate Wavelength Conversion and Subcarrier Multiplexed Addressing," *OFC 1999, Conference Digest*, pp. 162-164.

Blumenthal, D.J. et al.; "WDM Optical IP Tag Switching with Packet-Rate Wavelength Conversion and Subcarrier Multiplexed Addressing," *OFC 1999, Conference Digest*, pp. 162-164, 1999.

Lee, J. et al.; "Secure Communication Using Chaos," *Globe-com 1995*, pp. 1183-1187, Singapore, Nov. 14-16, 1995.

Bennett, Charles H.; "Experimental Quantum Cryptography," *Journal of Cryptology*, vol. 5, pp. 3 thru 28, (1992).

Faist, J. et al.; "High-Power Continuous-Wave Quantum Cascade Lasers," *IEEE Journal of Quantum Electronics*, vol. 34, No. 2, pp. 336-343, Feb., 1998.

Guillemot, Christian; "Optical Packet Switching for SDM High Speed Backbones," *Power Point Presentation at 24th European Conference on Optical Communication*, Madrid, Spain, pp. 1-43, Sep. 20-24, 1998.

Gambini, Piero et al.; "Transparent Optical Packet Switching: Network Architecture and Demonstrators in the KEOPS Project," *IEEE Journal on Selected Areas in Communications*, vol. 16, No. 7, pp. 1245-1259, Sep., 1998.

Hunter, David K.; "WASPNET: A Wavelength Switched Packet Network," *IEEE Communications Magazine*, pp. 120-129, Mar., 1999.

Kato, K. et al.; "32x32 Full-Mesh (1024 Path) Wavelength-Routing WDM Network Based on Uniform Loss Cyclic Frequency Arrayed-Waveguide Grating," *Electronics Letters*, vol. 36, No. 15, pp. 1294-1296, Jul. 20, 2000.

Takada, K. et al.; "480 Channel 10 GHz Spaced Multi/Demultiplexer," *Electronics Letters*, vol. 35, No. 22, pp. 1964-1966, Oct. 28, 1999.

Neber, S. et al.; "Tunable Laser Diodes with Type II Superlattice in the Tuning Region," *Semiconductor Science Technology*, vol. 13, pp. 801-805, 1998.

Chan, M. et al.; "The Effect of Carrier-Induced Change on the Optical Properties of AlGaAs-GaAs Intermixed Quantum Wells," *IEEE Journal on Selected Topics in Quantum Electronics*, vol. 4, No. 4, pp. 685-694, Jul./Aug., 1998.

Shim, J. et al.; "Refractive Index and Loss Changes Produced by Current Injection in InGaAs(P)InGaAsP Multiple Quantum-Well (MQW) Waveguides," *IEEE Journal on Selected Topics in Quantum Electronics*, vol. 1, No. 2, pp. 408-415, Jun., 1995.

Mason, B. et al.; "Widely Tunable Sampled Grating DBR Laser with Integrated Electroabsorption Modulator," *IEEE Photonics Technology Letters*, vol. 11, No. 6, pp. 638-640, Jun. 1999.

* cited by examiner

FIG. 1

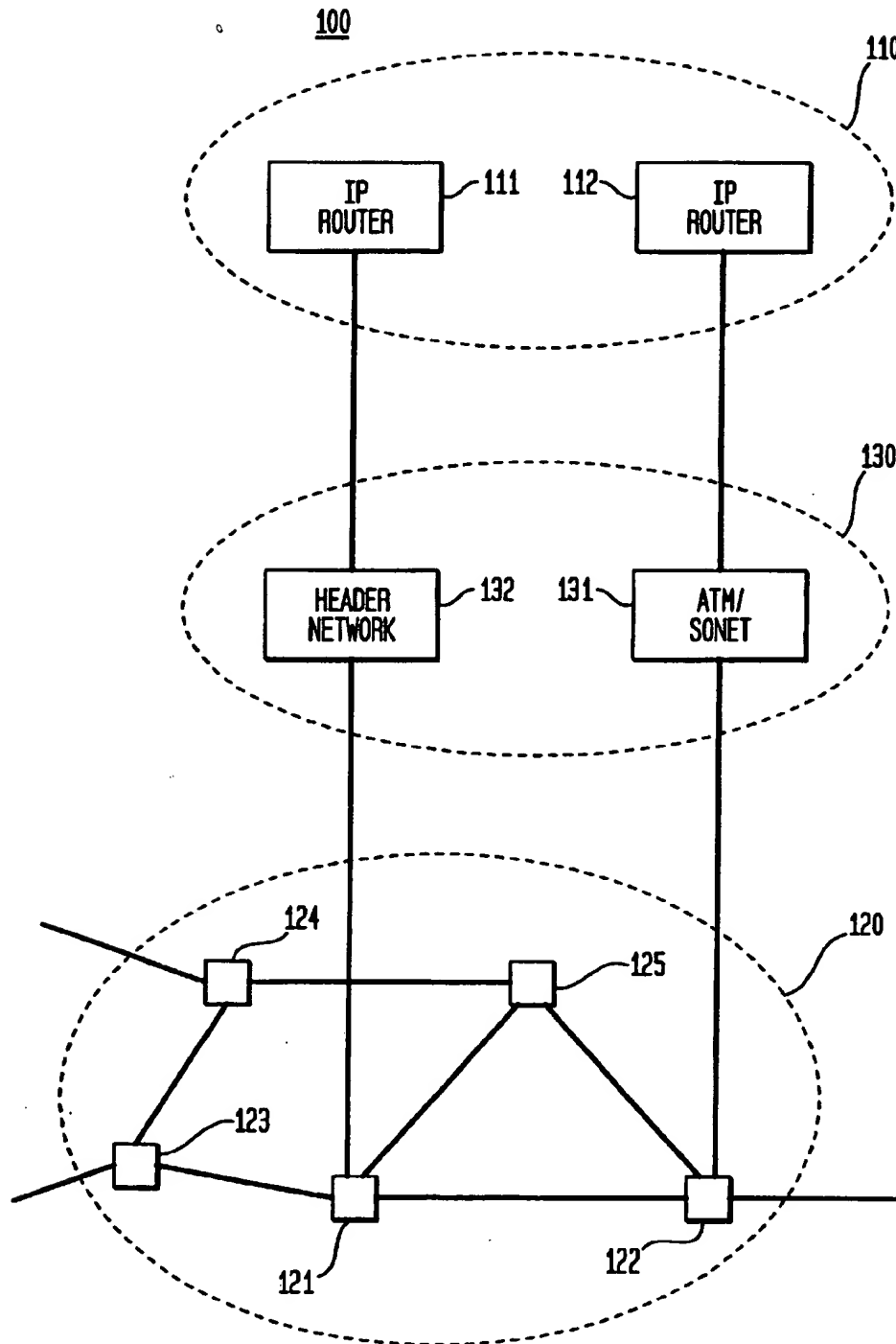


FIG. 2

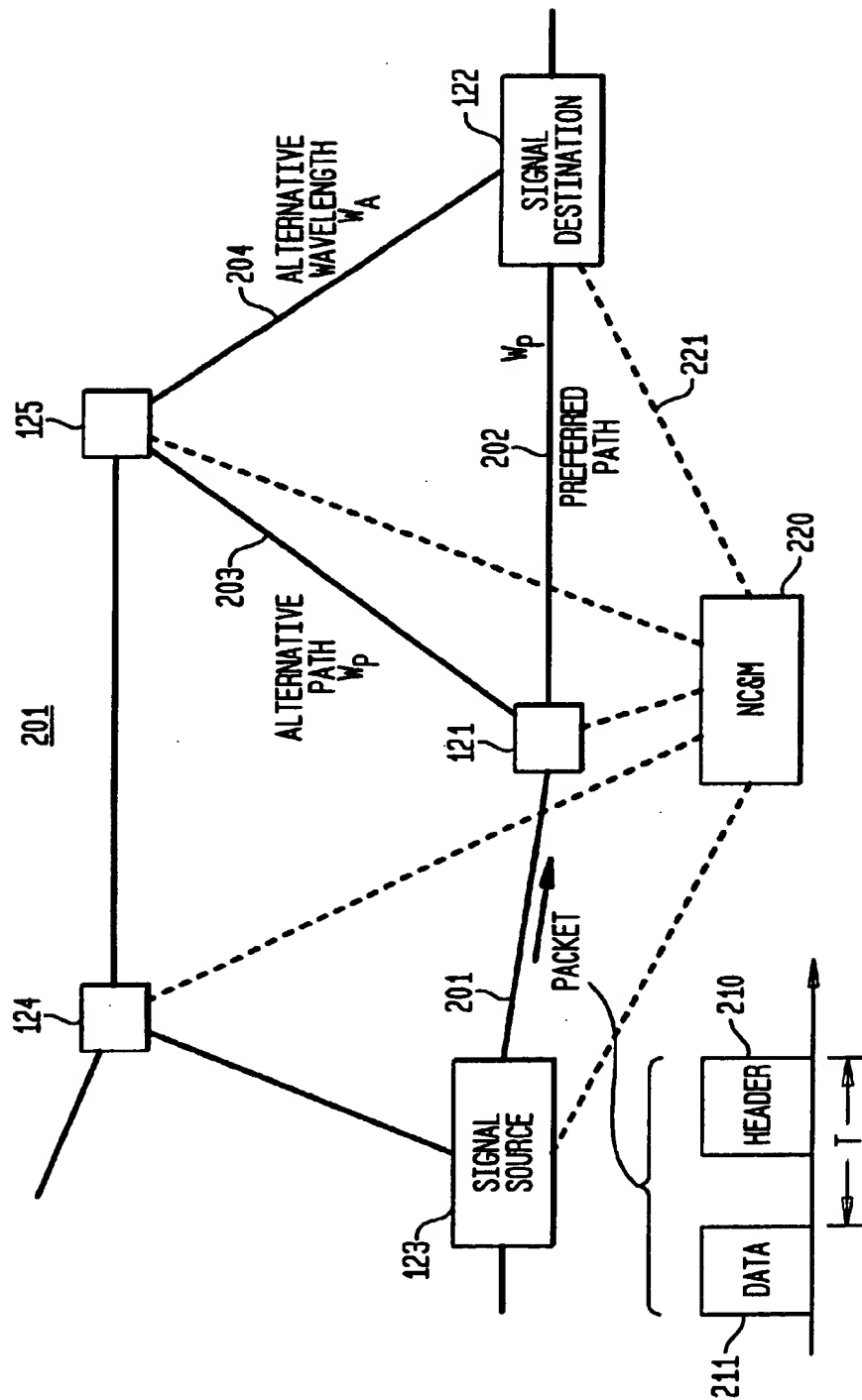


FIG. 3

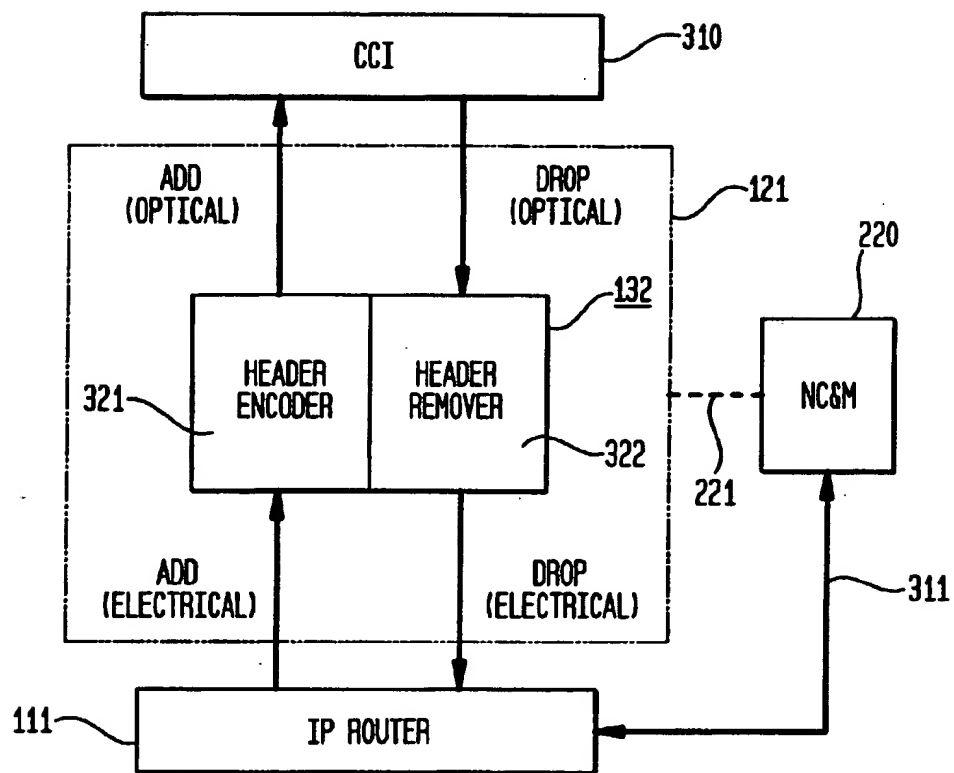
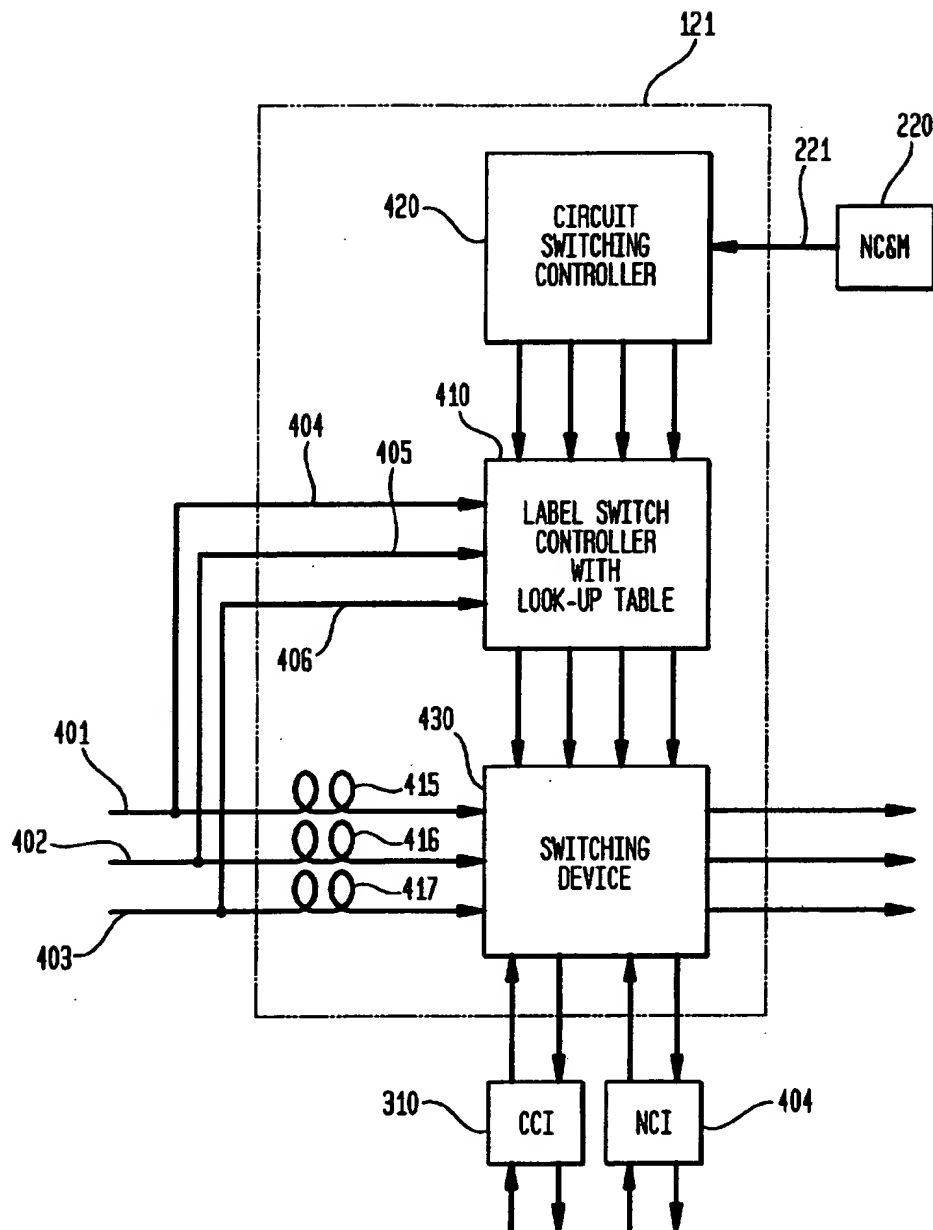


FIG. 4



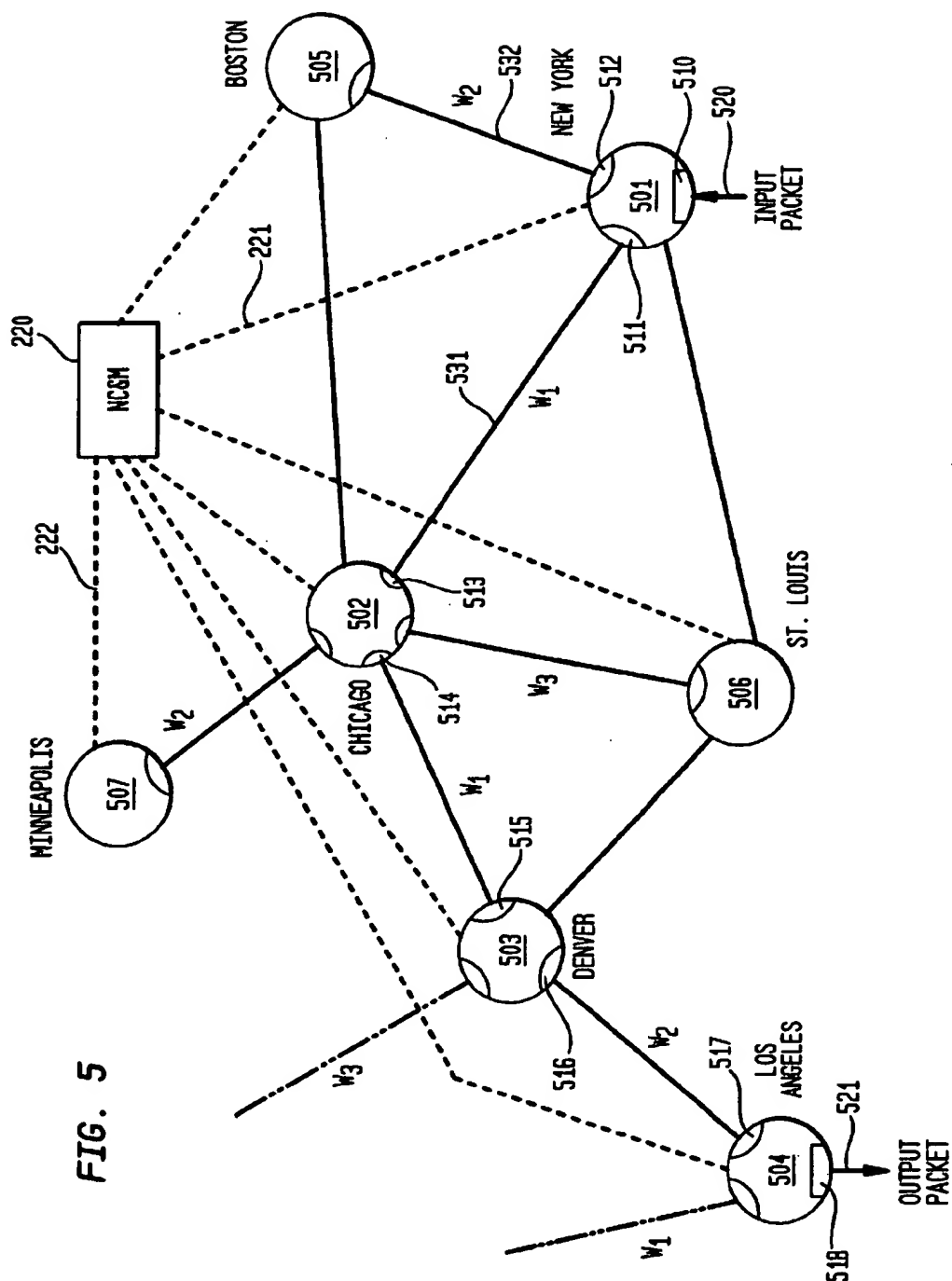


FIG. 6

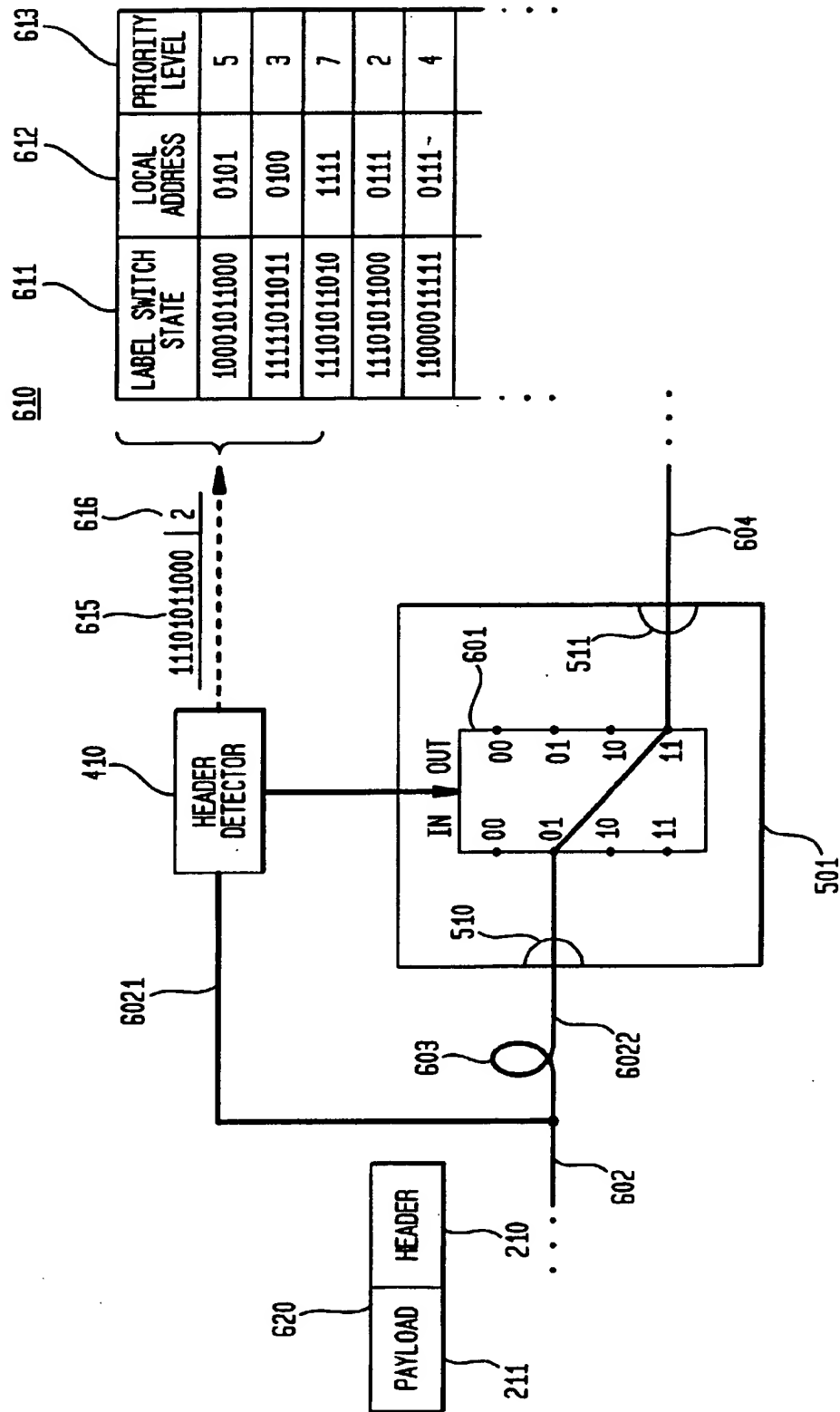


FIG. 7

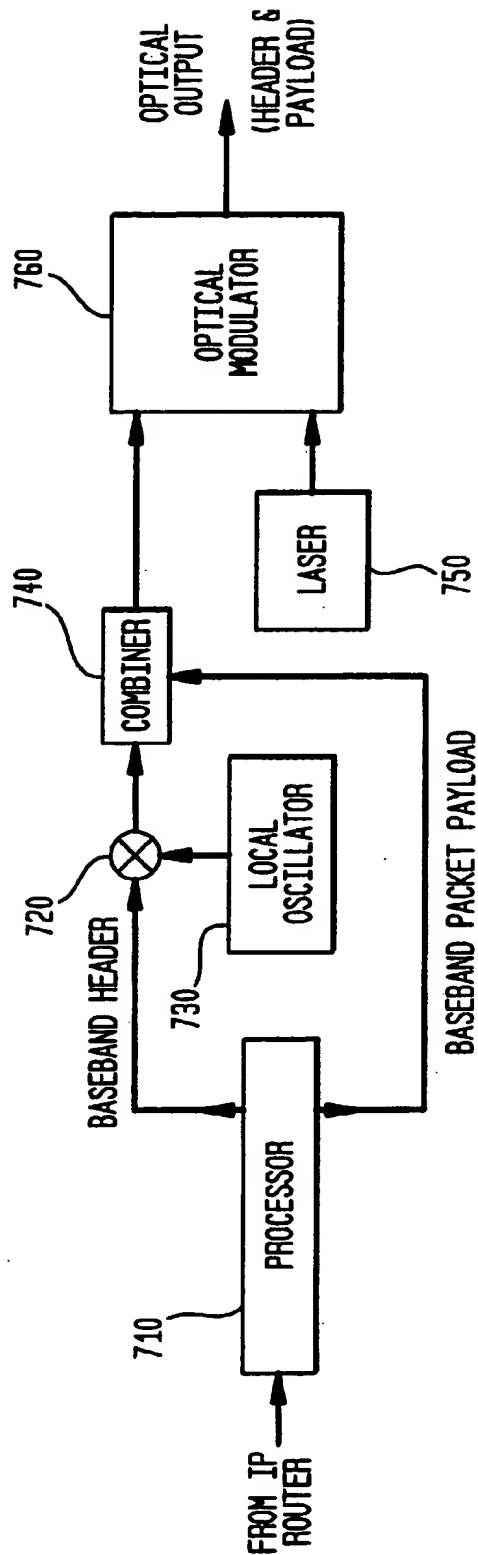


FIG. 8

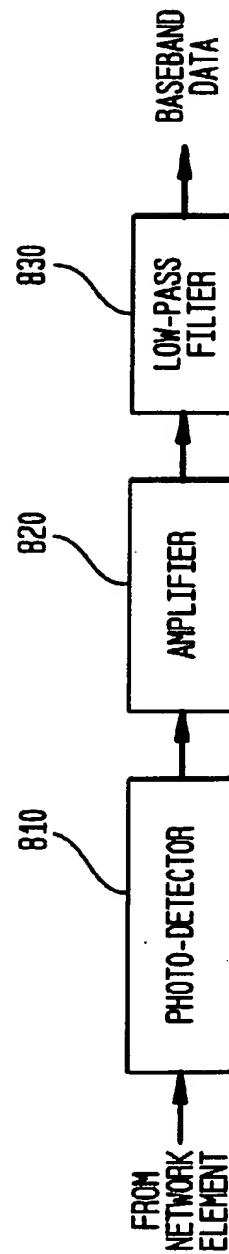
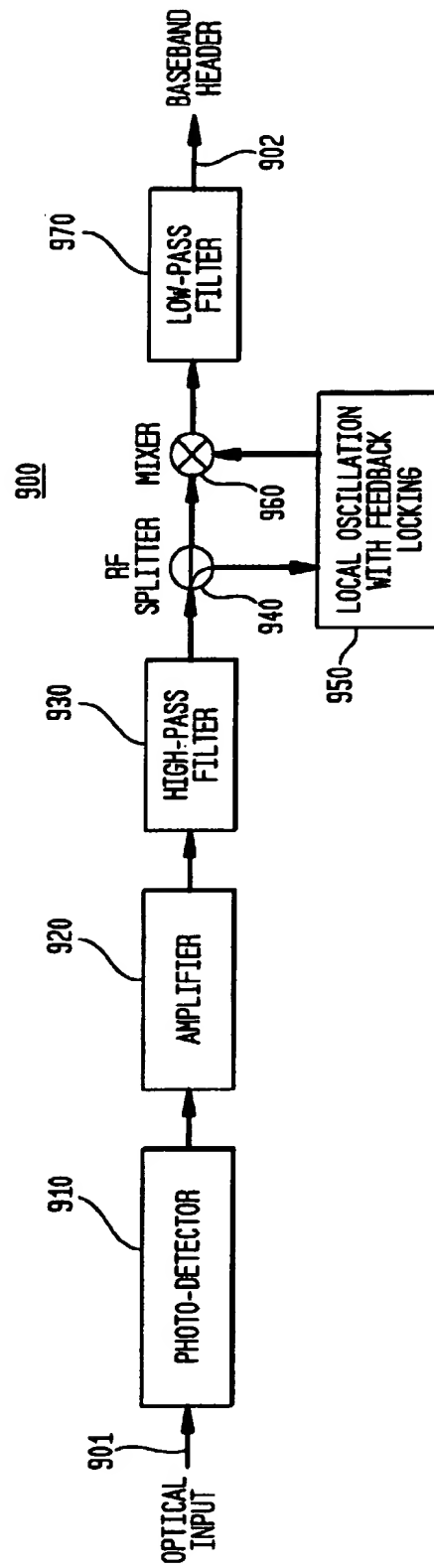


FIG. 9



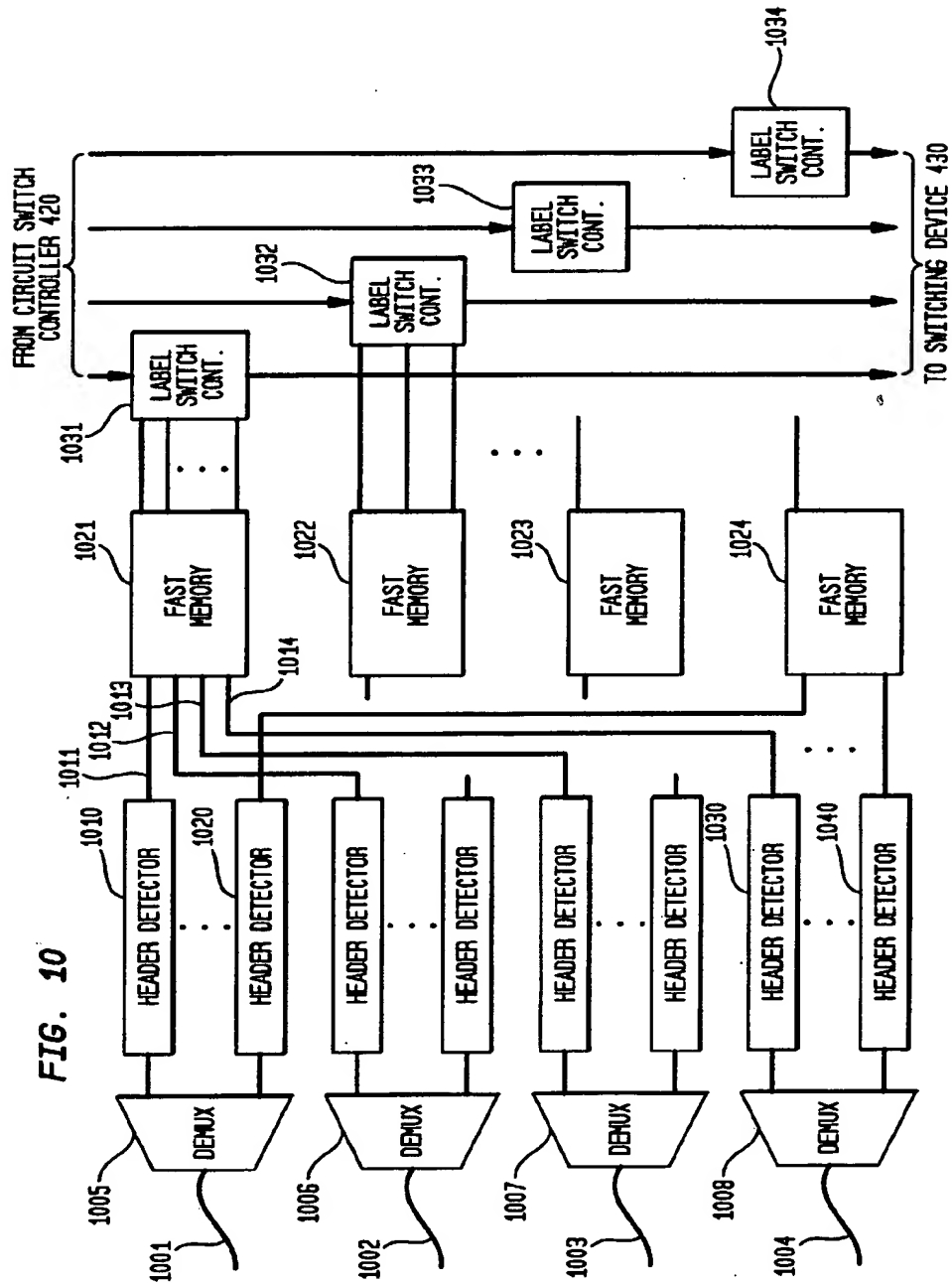
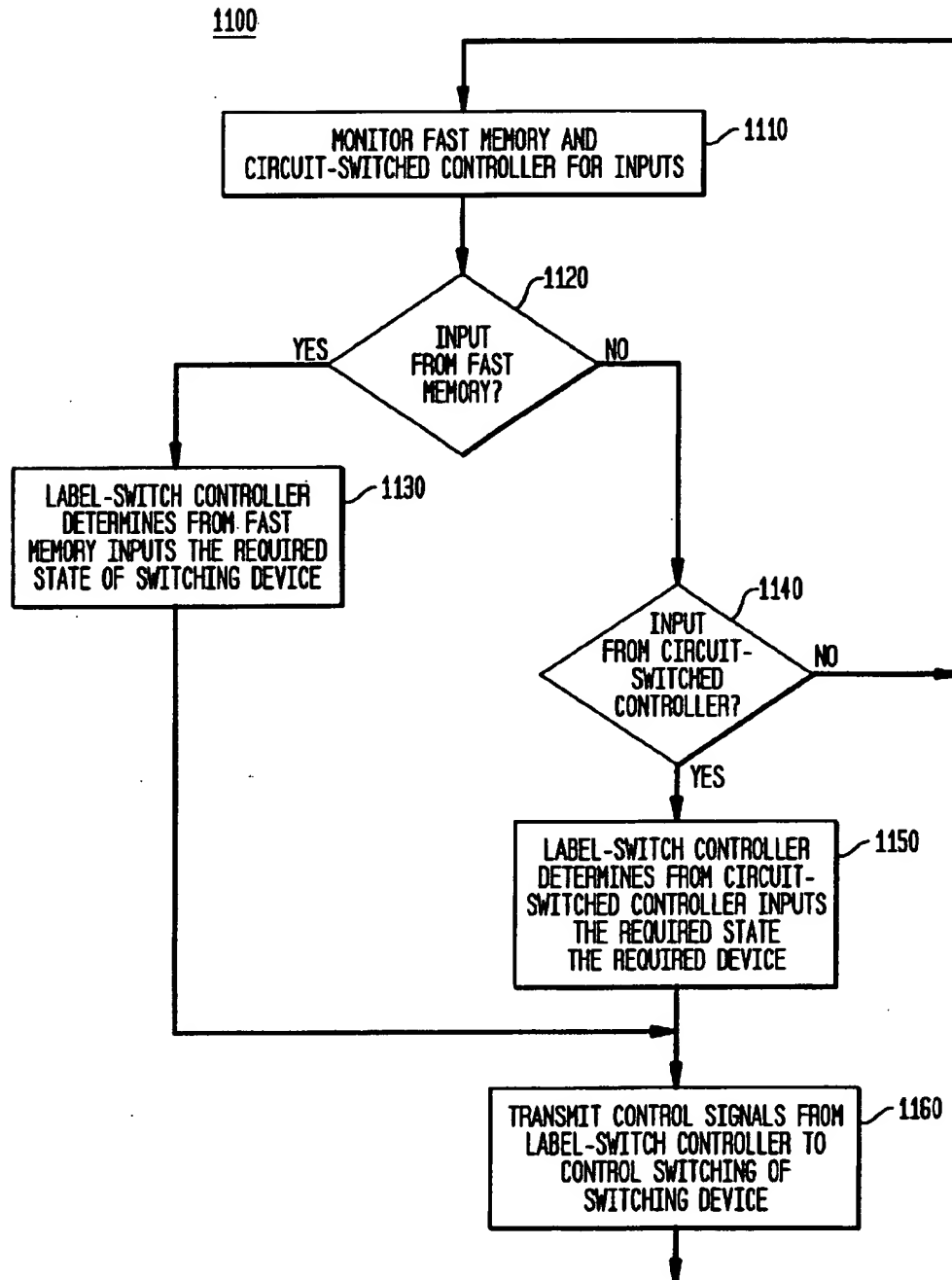
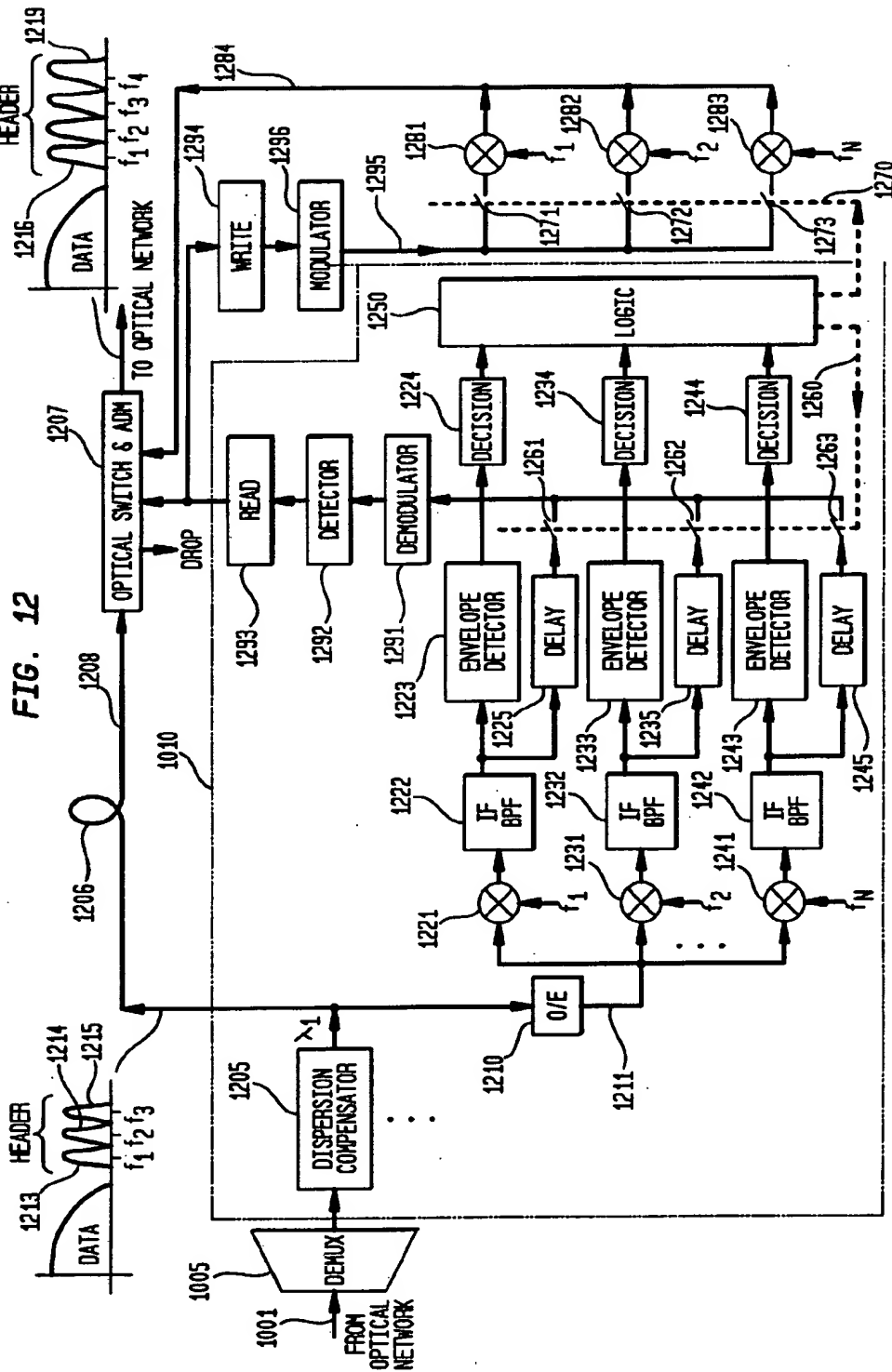


FIG. 11





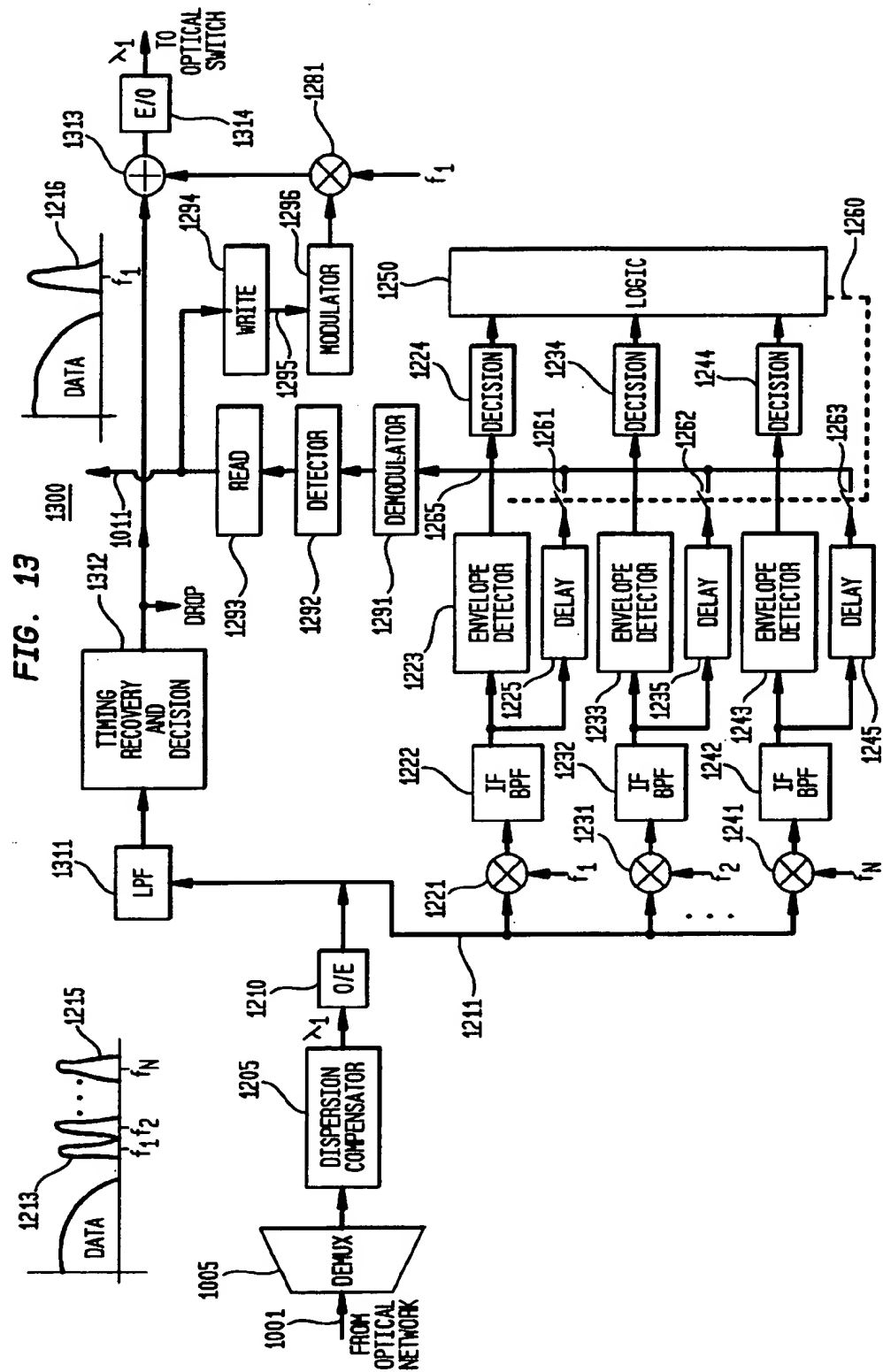


FIG. 14

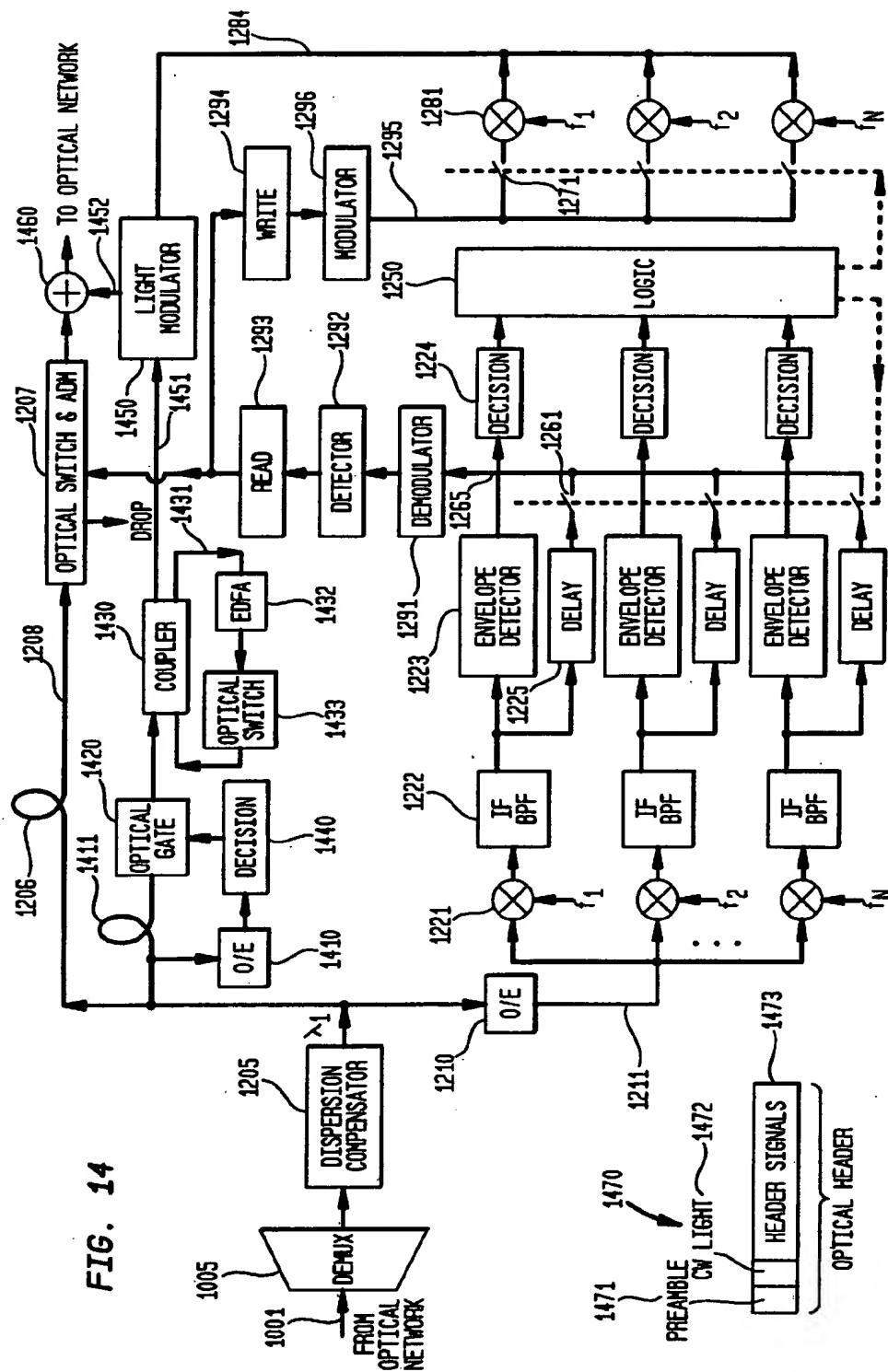
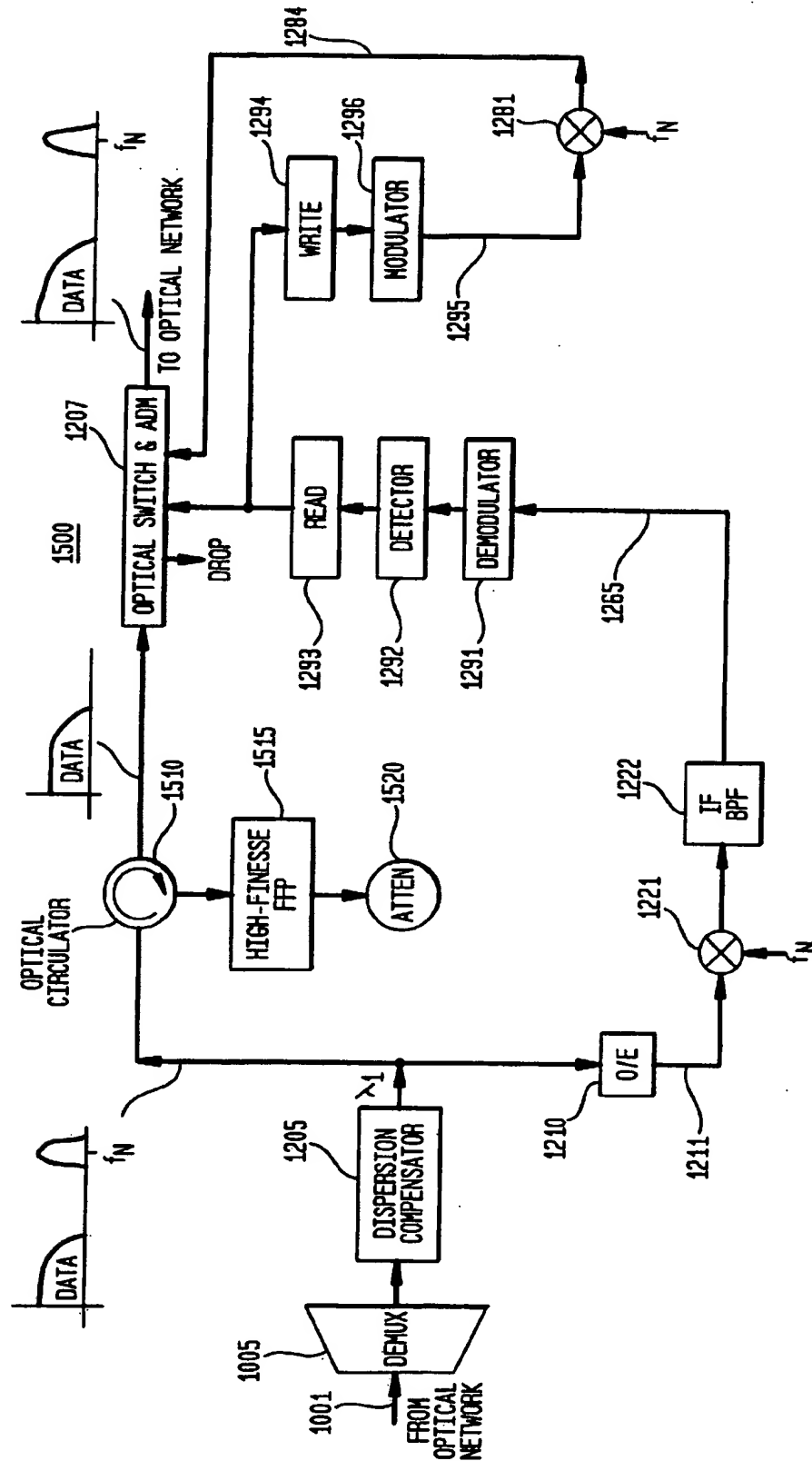


FIG. 15



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HIGH-THROUGHPUT, LOW-LATENCY NEXT GENERATION INTERNET NETWORKS USING OPTICAL LABEL SWITCHING AND HIGH-SPEED OPTICAL HEADER GENERATION, DETECTION AND REINSERTION

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of application Serial No. 09/118,437 filed Jul. 17, 1998 now U.S. Pat. No. 6,111,673, as well as a non-provisional application of provisional application Ser. No. 60/104,443 filed Oct. 16, 1998.

BACKGROUND OF THE DISCLOSURE

1. Field of the Invention

This invention relates to optical communication systems and, more particularly, to an optical system which accommodates network traffic with high throughput and low latency and effects high-speed header detection and generation.

2. Description of the Background Art

Recent research advances in optical Wavelength Division Multiplexing (WDM) technology have fostered the development of networks that are orders of magnitude higher in transmission bandwidth than existing commercial networks. While such an increase in throughput is impressive on its own, a corresponding decrease in network latency must also be achieved in order to realize the Next Generation Internet (NGI) vision of providing the next generation of ultra high speed networks that can meet the requirements for supporting new applications, including national initiatives. Towards this end, current research efforts have focused on developing an ultra-low latency Internet Protocol (IP) over WDM optical packet switching technology that promises to deliver the two-fold goal of both high throughput with low latency. Such efforts, while promising, have yet to fully realize this two-fold goal.

There are a number of challenging requirements in realizing such IP/WDM networks. First, the NGI network must inter-operate with the existing Internet and avoid protocol conflicts. Second, the NGI network must provide not only ultra low-latency, but must take advantage of both packet-switched (that is, bursty) IP traffic and circuit-switched WDM networks. Third, it is advantageous if the NGI network does not depend upon precise synchronization between signaling and data payload. Finally, a desired objective is that the NGI network accommodates data traffic of various protocols and formats so that it is possible to transmit and receive IP as well as non-IP signals without the need for complicated synchronization or format conversion.

Comparison with Other Work

The Multi-Wavelength-Optical Network (MONET) system, as reported in the article "MONET: Multi-Wavelength Optical Networking" by R. E. Wagner, et al. and published in the Journal of Lightwave Technology, Vol. 14, No. 6, June 1996, demonstrated a number of key milestones in optical network including transparent transmission of multi-wavelength through more than 12 reconfigurable network elements spread over the national scale fiber distance. The network, however, is circuit-switched and suffers inefficiency in accommodating bursty traffic. The typical connection setup time from request to switching is a few seconds, limited by capabilities of both Network Control &

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Management (NC&M) and hardware. Recent efforts within the MONET program to improve on the efficiency concentrated on the "Just-in-Time signaling" scheme. This method utilizes embedded 1510 nm NC&M signaling which precedes the data payload by an estimated delay time. This estimation must be accurately made for each network configuration for every wavelength in order to synchronize the signaling header and switching of the payload.

In accordance with the present invention, the optical packet header is carried over the same wavelength as the packet payload data. This approach mitigates the issue of header and payload synchronization. Furthermore, with a suitable use of optical delay at each intermediate optical switch, it eliminates the need to estimate the initial burst delay by incorporating the optical delay directly at the local switches. This makes a striking difference with Just-In-Time signaling in which the delay at each switch along the path needs to be known ahead of time and must be entered in the calculation for the total delay. Lastly, there is little time wasted in requesting a connection time and actually achieving a connection. In comparison to a few second delays seen in MONET, the present inventive subject matter reduces the delay to minimal, only limited by the actual hardware switching delays at each switch. The current switching technology realizes delays of only several microseconds, and shorter delays will be possible in the future. Such a short delay can be incorporated by using an optical fiber delay line at each network element utilizing switches. The present inventive subject matter achieves the lowest possible latency down to the fundamental limit of the hardware, and no lower latency can be achieved by any other technique.

The Optical Networks Technology Consortium (ONTC) results were reported in the article "Multiwavelength Reconfigurable WDM/ATM/SONET Network Testbed" by Chang et al. and published in the Journal of Lightwave Technology, Vol. 14, No. 6, June 1996. Both Phase I (155 Mb/s, 4-wavelength) and Phase II (2.5 Gb/s, 8-wavelength) of the ONTC program were configured on a Multihop ATM-based network. While such an ATM based architecture added a large overhead and excluded the possibility of a single-hop network, the packet/header signaling was made possible by utilizing the isochronous ATM cell itself. This communication of NC&M information is made through the same optical wavelength, potentially offering similar benefits as with the technique of the present invention. However, the inventive technique offers a number of significant advantages over the ATM-based signaling. First, the inventive technique offers a single hop connection for the payload without the need to convert to electrical signals and buffer the packets. Second, it offers far more efficient utilization of the bandwidth by eliminating excessive overheads. Third, it allows strictly transparent and ultra-low latency connections.

The DARPA sponsored All-Optical-Network (AON) Consortium results were reported in an article entitled "A Wideband All-Optical WDM Network", by I. P. Kaminow et al. and published in the IEEE Journal on Selected Areas of Communication, Vol. 14, No. 5, June 1996. There were actually two parts of the AON program: WDM as reported in the aforementioned article, and TDM reported in a companion paper in the same issue. First the WDM part of the AON program is first discussed, followed by the TDM part.

The AON architecture is a three-level hierarchy of subnetworks, and resembles that of LANs, MANs, and WANs seen in computer networks. The AON provides three basic services between Optical Terminals (OTs): A, B, and C services. A is a transparent circuit-switched service, B is

a transparent time-scheduled TDM/WDM service, and C is a non-transparent datagram service used for signaling. The B service uses a structure where a 250 microsecond frame is used with 128 slots per frame. Within a slot or group of slots, a user is free to choose the modulation rate and format. The B-service implemented on the AON architecture is closest to the IP over WDM which is the subject matter of the present invention. However, the separation of NC&M signaling in the C-service with the payload in the B-service requires careful synchronization between the signaling header and the payload. This requirement becomes far more stringent as the 250 microsecond frame is used with 128 slots per frame with arbitrary bit rates. Not only the synchronization has to occur at the bit level, but this synchronization has to be achieved across the entire network. The scalability and interoperability are extremely difficult since these do not go in steps with the network synchronization requirement. The present inventive subject matter requires only that the payload and the header are transmitted and received simultaneously, inter-operates with existing IP and non-IP traffic, and offers scalability.

TDM efforts are aimed at 100 Gb/s bit rates. In principle, such ultrafast TDM networks have the potential to provide truly flexible bandwidth on demand at burst rates of 100 Gb/s. However, there are significant technological challenges behind such high bit rate systems mainly related to nonlinearities, dispersion, and polarization degradations in the fiber. While the soliton technologies can alleviate some of the difficulties, it still requires extremely accurate synchronization of the network—down to a few picoseconds. In addition, the header and the payload must have the identical bit rates, and as a consequence, bit-rate transparent services are difficult to provide. The subject matter in accordance with the present invention does not depend on precise synchronization, relies on no 100 Gb/s technologies, and offers transparent services.

The Cisco Corporation recently announced a product based on Tag-Switching and the general description of Cisco's Tag-Switching is available at the world-wide-web site, (<http://www.cisco.com/warp/public/732/tag/>). Cisco's (electronic) Tag Switching assigns a label or "tag" to packets traversing a network of routers and switches. In a conventional router network, each packet must be processed by each router to determine the next hop of the packet toward its final destination. In an (electronic) Tag Switching network, tags are assigned to destination networks or hosts. Packets then are switched through the network with each node simply swaps tags rather than processing each packet. An (electronic) Tag Switching network will consist of a core of (electronic) tag switches (either conventional routers or switches), which connect to (electronic) tag edge routers on the network's periphery. (Electronic) Tag edge routers and tag switches use standard routing protocols to identify routes through the network. These systems then use the tables generated by the routing protocols to assign and distribute tag information via a Tag Distribution Protocol. Tag switches and tag edge routers receive the Tag Distribution Protocol information and build a forwarding database. The database maps particular destinations to the tags associated with those destinations and the ports through which they are reachable.

When a tag edge router receives a packet for forwarding across the tag network, it analyzes the network-layer header and performs applicable network layer services. It then selects a route for the packet from its routing tables, applies a tag and forwards the packet to the next-hop tag switch.

The tag switch receives the tagged packet and switches the packet based solely on the tag, without re-analyzing the

network-layer header. The packet reaches the tag edge router at the egress point of the network, where the tag is stripped off and the packet delivered. After Cisco made its announcement about (Electronic) Tag Switching, the IETF (Internet Engineering Task Force) has recommended a MPLS (Multi-protocol Label Switching) to implement standardized, vendor-neutral (electronic) tag-switching function in routers and switches, including ATM switches.

A number of features in the Cisco's (electronic) Tag Switching is similar to the Optical Tag Switching which is the subject matter of the present invention, with the features aimed at the similar goals of simplifying the processing required for packet routing. The key differences are as follows. First, the optical tag switching is purely optical in the sense that both tag and data payload are in an optical form. While each plug-and-play module (a component of the present inventive system) senses the optical tag, the actual packet does not undergo optical-to-electrical conversion until it comes out of the network. The Cisco's (electronic) Tag Switching will be all electrical, and applies electronic detection, processing, and retransmission to each packet at each router. Secondly, the Optical Tag Switching of the present invention achieves lowest possible latency and does not rely on utilizing buffers. Electronic tag switching will have far greater latency due to electronic processing and electronic buffering. Thirdly, the Optical Tag Switching of the present invention utilizes path deflection and/or wavelength conversion to resolve blocking due to contention of the packets, whereas the Electronic Tag Switching will only utilize electronic buffering as a means to achieve contention resolution at the cost of increased latency, and the performance is strongly dependent on packet size. The present invention covers packets of any length. Lastly, the Optical Tag Switching of the present invention achieves a strictly transparent network in which data of any format and protocol can be routed so long as it has a proper optical tag. Hence the data can be digital of any bit rate and modulation formats. The Electronic Tag Switching requires that data payload to have the given digital bit rate identical to the electronic tag since the routers must buffer them electronically.

Another representative technology that serves as background to the present invention is the so-called Session Deflection Virtual Circuit Protocol (SDVC), which is based on deflection routing method. The paper entitled "The Manhattan Street Network", by N. F. Maxemchuk as published in the Proceedings on IEEE Globecom '85, pp 255-261, December 1985, discusses that when two packets attempt to go to the same destination, one packet can be randomly chosen for the preferred output link and the other packet is "deflected" to the non-preferred link. This means that packets will occasionally take paths that are not shortest paths. The deflection method utilized by the present invention does not 'randomly' select the packet to go to the most preferred path; rather, it attempts to look into the priorities of the packets, and send the higher priority packet to be routed to the preferred path. The packets will be deflected if they have lower priorities; however, both 'path deflection' and 'wavelength deflection' are utilized. The path deflection is similar to conventional SDVC in that the optical packet will be simply routed to the path of the next preference at the same wavelength. The wavelength deflection allows the optical packet to be routed to the most preferred path but at a different wavelength. This wavelength deflection is achieved by wavelength conversion at the network elements. Partially limited wavelength conversion is utilized, meaning not all wavelengths will be available as destination wave-

lengths for a given originating wavelength. The wavelength deflection allows resolution of blocking due to wavelength contentions without increasing the path delay. The combination of path and wavelength deflections offers sufficiently large additional connectivities for resolving packet contentions; however, the degree of partial wavelength conversion can be increased when the blocking rate starts to rise. Such scalability and flexibility of the network is not addressed by conventional SDVC.

Besides the foregoing overall system considerations elucidated above, there is also the issue of how to effectively detect and/or re-insert a header which is combined with a data payload for propagation over the network using the same optical wavelength. The primary focus in the literature has been on a technique for combining sub-carrier headers with a baseband data payload. The very first two articles addressing this issued were published in 1992 by A. Bidman et. al., who combined a 2.56 Gb/s data payload with a 40 Mb/s header on 3 GHz carrier [A. Budman, E. Eichen, J. Schalafer, R. Olshansky, and F. McAleavey, "Multigigabit optical packet switch for self-routing networks with subcarrier addressing," Technical Digest, paper Tu04, pp.90-91, OFC'92], and W. I. Way et al., who combined a 2.488 Gb/s data payload with a tunable microwave pilot tone (tuned between 2.520 and 2.690 GHz) to route SONET packet in a WDM ring network via acousto-optical tunable filter [W. I. Way, D. A. Smith, J. J. Johnson, H. Izadpanah, and H. Johnson, "Self-routing WDM high-capacity SONET ring network," Technical Digest, paper Tu02, pp.86-87, OFC'92, and W. I. Way, D. A. Smith, J. J. Johnson, and H. Izadpanah, "A self-routing WDM high-capacity SONET ring network," IEEE Photonics Technology Letters, vol.4, pp.402-404, April 1992.2,3]. Both of articles used a single laser diode to carry the data payload and sub-carrier header. This technique has also been extensively studied in a local-area DWDM optical packet-switched network [R. T. Hofmeister, L. G. Katzovsky, C. L. Lu, P. Poggiolini, and F. Yang, "CORD: optical packet-switched network tested," Fiber and Integrated Optics, vol.16, pp.199-219, 1997], and several other all-optical networks [E. Park and A. E. Willner, "Network demonstration of self-routing wavelength packets using an all-optical wavelength shifter and QPSK subcarrier routing control," IEEE Photonics Technology Letters, vol.8, pp.938-940, 1996; and M. Shell, M. Vaughn, A. Wang, D. J. Blumenthal, P. J. Rigole, and S. Nilsson, "Experimental demonstration of an all-optical routing node for multihop wavelength routed networks," IEEE Photonic Technology Letters, vol.8, pp.1391-1393, 1996].

Instead of combining a sub-carrier headers with the data payload in the electrical domain, they have also been combined in the optical domain by using two laser diodes at different wavelengths [B. H. Wang, K. Y. Yen, and W. I. Way, "Demonstration of gigabit WDMA networks using parallel-processed sub-carrier hopping pilot-tone (P³) signaling technique," IEEE Photonics Technology Letters, vol.8, pp.933-934, July 1996].

However, using two wavelengths to transport data payload and header separately may not be practical in the following sense: in an all-optical DWDM network, it is preferred that the header, which may contain network operations information, travels along the same routes as data payload so that it can truthfully report the updated status of the data payload. If the header and the data payload were carried by different wavelengths, they could be routed in the network with entirely different paths, and the header may not report what the data payload has really experienced. Therefore, although it is preferred that the sub-carrier header

and the data payload be carried by the same wavelength, the art is devoid of such teachings and suggestions.

The sub-carrier pilot-tone concept presented in Wang et al. was extended to multiple pilot tones by Shieh et al. [W. Shieh and A. E. Willner, "A wavelength routing node using multifunctional semiconductor optical amplifiers and multiple-pilot-tone-coded subcarrier control headers," IEEE Photonics Technology Letters, vol.9, pp.1268-1270, September 1997.], mainly for the purpose of increasing the number of network addresses.

Recently, consideration has been given to 'header replacement' for the high-throughput operation in a packet-switched network in which data paths change due to link outages, output-port contention, and variable traffic patterns. Moreover, header replacement could be useful for maintaining protocol compatibility at gateways between different networks. However, the only method which has been reported is for time-division-multiplexed header and data payload requires an extremely high accuracy of timing synchronization among network nodes [X. Jiang, X. P. Chen, and A. E. Willner, "All optical wavelength independent packet header replacement using a long CW region generated directly from the packet flag," IEEE Photonics Technology Letters, vol.9, pp.1638-1640, November 1998].

From this overview of the art pertaining to details of header generation and detection, it is readily understood that the art is devoid of teachings and suggestions wherein sub-carrier multiplexed packet data payload and multiple sub-carrier headers (including old and new ones) are deployed so that a >2.5 Gbps IP packet can be routed through a national all-optical DWDM network by the (successive) guidance of these sub-carrier headers, with the total number of sub-carrier headers that can be written in is in the range of forty or more.

SUMMARY OF THE INVENTION

The present invention utilizes a unique optical signaling header technique applicable to optical networks. Packet routing information is embedded in the same channel or wavelength as the data payload so that both the header and data information propagate through the network with the same path and the associated delays. However, the header routing information has sufficiently different characteristics from the data payload so that the signaling header can be detected without being affected by the data payload and that the signaling header can also be stripped off without affecting the data payload. The inventive subject matter allows such a unique signal routing method to be overlaid onto the conventional network elements in a modular manner, including the insertion, detection and processing of the optical header.

In accordance with a broad method aspect of the present invention commensurate with the overall NGI system, a method for propagating a data payload from an input network element to an output network element in a wavelength division multiplexing system composed of a plurality of network elements, given that the data payload has a given format and protocol, includes the following steps: (a) adding a header to the data payload prior to inputting the data payload to the input network element to produce an optical signal, the header having a format and protocol and being indicative of the local route through each of the network elements for the data payload and the header, the format and protocol of the data payload being independent of the format and protocol of the header; and (b) detecting the header at each of the network elements as the data payload and header

propagate through the WDM network, wherein the header is composed of a header signal being conveyed by a distinct carrier frequency such that the spectrum of the header signal occupies a frequency band above the data payload, such that the step of detecting includes (i) opto-electrically converting the optical signal to detect header information in the header signal, and (ii) reading the header information to produce a switch control signal to route the incoming optical signal; moreover, the method further includes after the step of detecting the steps of (iii) optically processing the optical signal to delete the header signal and recover only the data payload, and (iv) inserting a new header signal into the optical signal in place of the deleted header signal.

In accordance a broad system aspect of the present invention for an individual network element, a system for detecting and replacing the header includes the following components: (a) an opto-electrical converter, responsive to the optical signal, for converting the optical signal to detect header information in the header signal, (b) means, responsive to the converter, for reading the header information to produce a switch control signal to route the optical signal, (c) an optical processor, responsive to the optical signal, for deleting the header signal, and (d) means, coupled to the optical processor and the means for reading, for inserting a new header signal into the optical signal in place of the deleted header signal.

BRIEF DESCRIPTION OF THE DRAWINGS

The teachings of the present invention can be readily understood by considering the following detailed description in conjunction with the accompanying drawings, in which:

FIG. 1 is a pictorial representation of a general network illustrating the coupling between the optical and electrical layers of the network;

FIG. 2 illustrates the optical layer of the network of FIG. 1 showing the relationship between the optical signal header and data payload, and the use of the header/payload in network setup;

FIG. 3 is a high-level block diagram an optical transmitter in accordance with the present invention for header encoding;

FIG. 4 is a high-level block diagram an optical receiver in accordance with the present invention for header decoding;

FIG. 5 is illustrative of a WDM circuit-switched backbone network;

FIG. 6 illustrates a network element of FIG. 1 with its embedded switch and the use of local routing tables;

FIG. 7 depicts a block diagram of an illustrative embodiment of a header encoder circuit for the Plug-&-Play module of FIG. 3;

FIG. 8 depicts a block diagram of an illustrative embodiment of a header remover circuit for the Plug-&-Play module of FIG. 3;

FIG. 9 depicts a block diagram of an illustrative embodiment of a header detector circuit for the Plug-&-Play module of FIG. 4;

FIG. 10 depicts a block diagram for a more detailed embodiment of FIG. 4 wherein the label-switch controller includes interposed demultiplexers, and header detectors and fast memory;

FIG. 11 is a flow diagram for the processing effected by each label-switch controller of FIG. 10;

FIG. 12 is a block diagram of circuitry for detecting the active header signal and for inserting a new active header signal without local injection of light;

FIG. 13 is a block diagram of re-set circuitry for deleting all incoming header signals, and for inserting a new original header signal;

FIG. 14 is a block diagram of circuitry for detecting the active header signal and for inserting a new active header signal using the local injection of light; and

FIG. 15 is a block diagram of circuitry for removing a single header signal and replacing the removed header signal with a new header signal.

To facilitate understanding, identical reference numerals have been used, where possible, to designate identical elements that are common to the figures.

DETAILED DESCRIPTION

In order to gain an insight into the fundamental principles in accordance with the present invention as well as to introduce terminology useful in the sequel, an overview is first presented, followed by an elucidation of an illustrative embodiment.

Overview

The present invention relates to a network for realizing low latency, high throughput, and cost-effective bandwidth-on-demand for large blocks of data for NGI applications. Cost-effective and interoperable upgrades to the network are realized by interposing portable 'Plug-and-Play' modules on the existing WDM network elements to effect so-called "WDM optical label switching" or, synonymously, "optical label switching". The invention impacts primarily the hardware for the NGI network from the network element design perspective.

As alluded to, the methodology carried out by the network and concomitant circuitry for implementing the network are engendered by a technique called WDM optical label-switching—defined as the dynamic generation of a routing path for a burst duration by an in-band optical signaling header. Data packets are routed through the WDM network using an in-band WDM signaling header for each packet. At a switching node, the signaling header is processed and the header and the data payload (1) may be immediately forwarded through an already existing flow state connection, or (2) a path can be setup for a burst duration to handle the header and the data payload. WDM label-switching enables highly efficient routing and throughput, and reduces the number of IP-level hops required by keeping the packets routing at the optical level to one hop as managed by the Network Control and Management (NC&M) which creates and maintains routing information.

The depiction of FIG. 1 shows the inter-relation between optical layer 120 and electrical layer 110 of generic network 100 as provided by intermediate layer 130 coupling the optical layer and the electrical layer. Electrical layer 110 is shown, for simplicity, as being composed of two conventional IP routers 111 and 112. Optical layer 120 is shown as being composed of network elements or nodes 121-125. Intermediate layer 130 depicts conventional ATM/SONET system 131 coupling IP router 112 to network element 122. Also shown as part of layer 130 is header network 132, which in accordance with the present invention, couples IP router 111 to network element 121. FIG. 1 pictorially illustrates the location of network 132 on a national-scale, transparent WDM-based backbone network with full interoperability and reconfigurability. It is important to emphasize at this point that the elements of FIG. 1 are illustrative of one embodiment in accordance with the

present invention; thus, for example, element 111 may, in another embodiment, be an ATM router or even a switch.

Now with reference to FIG. 2, optical layer 120 of FIG. 1 is shown in more detail including the basic technique, in accordance with the present invention, for setting up a fast connection in optical network 201, composed of network elements 121–125; the setup uses optical signaling header 210 for the accompanying data payload 211. This technique combines the advantages of circuit-switched based WDM and packet-switched based IP technologies. New signaling information is added in the form of an optical signal header 210 which is carried in-band within each wavelength in the multi-wavelength transport environment. Optical signaling header 210 is a label containing routing and control information such as the source, destination, priority, and the length of the packet, propagates through optical network 201 preceding data payload 211. Each WDM network element 121–125 senses optical signaling header 210, looks-up a connection table (discussed later), and takes necessary steps such as cross-connections, add, drop, or drop-and-continue. The connection table is constantly updated by continuous communication between NC&M 220 and WDM network elements 121–125. Data payload 211, which follows optical signaling header 210, is routed through a path in each network element (discussed later) as established by the connection. With the arrangement of FIG. 2, there is no need to manage the time delay between optical signaling header 210 and data payload 211, shown by T in FIG. 2, because each network element provides the optical delay needed for the short time required for connection setup within each network element via delay on an interposed fiber. Moreover, the format and protocol of the data payload is independent of that of the header, that is, for a given network whereas the format and protocol of the header are pre-determined, the format and the protocol of the data payload can be the same as or different from those of the header.

Each destination is associated with a preferred path which would minimize ‘the cost’—in FIG. 2, the overall path from source 123 to destination 122 includes paths 201 and 202 in cascade, both utilizing wavelength WP. This cost is computed based on the total propagation distance, the number of hops, and the traffic load. The preferred wavelength is defaulted to the original wavelength. For example, the preferred wavelength on path 202 is WP. If this preferred path at the default wavelength is already occupied by another packet, then network element 121 quickly decides if there is an available alternate wavelength WA through the same preferred path. This alternate wavelength must be one of the choices offered by the limited wavelength conversion in network element 121. If there is no choice of wavelengths which allows transport of the packet through the most preferred path, the next preferred path is selected (path deflection). For example, in FIG. 2, paths 203 and 204 in cascade may represent the alternative path. At this point, the preferred wavelength will default back to the original wavelength WP. The identical process of looking for an alternate wavelength can proceed if this default wavelength is again already occupied. In FIG. 2, path 203 is an alternative path with the same wavelength WP, and path 204 is an alternate path using alternate wavelength WA. In an unlikely case where there is no combination of path and wavelength deflection can offer transport of the packet, network element 121 will decide to drop the packet of lower priority. In other words, the new packet transport through the preferred path at the originating wavelength takes place by dropping the other packet of the lower priority which is already occupying the preferred path.

Network elements 121–125 are augmented with two types of so-called ‘Plug-and-Play’ modules to efficiently handle bursty traffic by providing packet switching capabilities to conventional circuit-switched WDM network elements 121–125 whereby signaling headers are encoded onto IP packets and are removed when necessary.

The first type of ‘Plug-and-Play’ module, represented by electro-optical element 132 of FIG. 1, is now shown in block diagram form in FIG. 3. Whereas conceptually module 132 is a stand-alone element, in practice, module 132 is integrated with network element 121 as is shown in FIG. 3; module 132 is interposed between compliant client interface (CCI) 310 of network element 121 and IP router 111 to encode optical signaling header 210 onto the packets added into the network via header encoder 321, and to remove optical signaling header 210 from the packets dropping out of the network via header remover 322.

Generally, encoding/removing module 132 is placed where the IP traffic is interfaced into and out of the WDM network, which is between the client interface of the network element and the IP routers. The client interfaces can be either a CCI-type or a non-compliant client interfaces (NCI)-type. At these interfaces, header encoder 321 puts optical header 210 carrying the destination and other information in front of data payload 211 as the IP signal is transported into network 201. Optical header 210 is encoded in the optical domain by an optical modulator (discussed later). Signaling header remover 322 deletes header 210 from the optical signal dropped via a client interface, and provides an electrical IP packet to IP router 111.

More specifically, module 132 accepts the electrical signal from IP router 111, converts the electrical signal to a desired compliant wavelength optical signal, and places optical header 210 in front of the entire packet. Module 132 communicates with NC&M 220 and buffers the data before optically converting the data if requested by NC&M 220. Module 132 employs an optical transmitter (discussed later) with the wavelength matched to the client interface wavelength. (As indicated later but instructive to mention here, module 132 is also compatible with NCI 404 of FIG. 4 since the wavelength adaptation occurs in the NCI; however, the bit-rate-compatibility of NCI wavelength adaption and the IP signal with optical headers must be established in advance.)

FIG. 4 depicts a second type of ‘Plug-and-Play’ module, optical element 410, which is associated with each WDM network element 121–125, say element 121 for discussion purposes. Module 410 is interposed between conventional network element circuit switch controller 420 and conventional switching device 430. Module 410 detects information from each signaling header 210 propagating over any fiber 401–403, as provided to module 410 by tapped fiber paths 404–406. Module 410 functions to achieve very rapid table look-up and fast signaling to switching device 430. Switch controller 420 is functionally equivalent to the conventional “craft interface” used for controlling the network elements; however, in this case, the purpose of this switch controller 420 is to accept the circuit-switched signaling from NC&M 220 and determine which control commands are to be sent to label switch controller 410 based on the priority. Thus, label switch controller 410 receives circuit-switched control signals from network element circuit switch controller 420, as well as information as derived from each signaling each header 210, and intelligently chooses between the circuit-switched and the label-switched control schemes. The switches (discussed later) comprising switching device 430 also achieve rapid switching. The

delay imposed by fibers 415, 416, or 417, which are placed in input paths 401–403 to switching device 430, are such that the delay is larger than the total time it takes to read signaling header 210, to complete a table look-up, and to effect switching. Approximately, a 2 km fiber provides 10 microsecond processing time. The types of WDM network elements represented by elements 121–125 and which encompass switching device 430 include: Wavelength Add-Drop Multiplexers (WADMs); Wavelength Selective Cross-connects (WSXCs); and Wavelength Interchanging Cross-connects (WIXCs) with limited wavelength conversion capabilities.

In operation, module 410 taps a small fraction of the optical signals appearing on paths 401–403 in order to detect information in each signaling header 210, and determine the appropriate commands for switching device 430 after looking up the connection table stored in module 410. The fiber delay is placed in paths 401–403 so that the packet having header 210 and payload 211 reaches switching device 430 only after the actual switching occurs. This fiber delay is specific to the delay associated with header detection, table look-up, and switching, and can typically be accomplished in about 10 microseconds with about 2 km fiber delay in fibers 415–417.

Packets are routed through network 201 using the information in signaling header 210 of each packet. When a packet arrives at a network element, signaling header 210 is read and either the packet (a) is routed to a new appropriate outbound port chosen according to the label routing look-up table, or (b) is immediately forwarded through an already existing label-switching originated connection within the network element. The latter case is referred to as “flow switching” and is supported as part of optical label-switching; flow switching is used for large volume bursty mode traffic.

Label-switched routing look-up tables are included in network elements 121–125 in order to rapidly route the optical packet through the network element whenever a flow switching state is not set-up. The connection set-up request conveyed by optical signaling header 210 is rapidly compared against the label-switch routing look-up table within each network element. In some cases, the optimal connections for the most efficient signal routing may already be occupied. The possible connection look up table is also configured to already provide an alternate wavelength assignment or an alternate path to route the signal. Providing a limited number of (at least one) alternative wavelength significantly reduces the blocking probability. The alternative wavelength routing also achieves the same propagation delay and number of hops as the optimal case, and eliminates the difficulties in sequencing multiple packets. The alternate path routing can potentially increase the delay and the number of hops, and the signal-to noise-ratio of the packets are optically monitored to eliminate any possibility of packets being routed through a large number of hops. In the case where a second path or wavelength is not available, contention at an outbound link can be settled on a first-come, first-serve basis or on a priority basis. The information is presented to a regular IP router and then is reviewed by higher layer protocols, using retransmission when necessary.

Routing Example

An illustrative WDM circuit-switched backbone network 500 for communicating packets among end-users in certain large cities in the United States is shown in pictorial form in FIG. 5—network 500 is first discussed in terms of its

conventional operation, that is, before the overlay of WDM optical label switching in accordance with the present invention is presented.

With reference to FIG. 5, it is supposed that New York City is served by network element 501, Chicago is served by network element 502, . . . , Los Angeles is served by network element 504, . . . , and Minneapolis by network element 507. (Network elements may also be referred to as nodes in the sequel.) Moreover, NC&M 220 has logical connections (shown by dashed lines, such as channel 221 to network element 501 and channel 222 to network element 507) to all network elements 501–507 via physical layer optical supervisory channels; there is continuous communication among NC&M 220 and network elements 501–507. NC&M 220 periodically requests and receives information about: (a) the general state of each network element (e.g., whether it is operational or shut down for an emergency); (b) the optical wavelengths provided by each network element (e.g., network element 501 is shown as being served by optical fiber medium 531 having wavelength W1 and optical fiber medium 532 having wavelength W2 which connect to network elements 502 (Chicago) and 505 (Boston), respectively); and (c) the ports which are served by the wavelengths (e.g., port 510 of element 501 is associated with an incoming client interface conveying packet 520, port 511 is associated with W1 and port 512 is associated with W2, whereas port 513 of element 502 is associated with W1).

Thus, NC&M 220 has stored at any instant the global information necessary to formulate routes to carry the incoming packet traffic by the network elements. Accordingly, periodically NC&M 220 determines the routing information in the form of, for example, global routing tables, and downloads the global routing tables to each of the elements using supervisory channels 221, 222, The global routing tables configure the ports of the network elements to create certain communication links. For example, NC&M 220 may determine, based upon traffic demand and statistics, that a fiber optic link from New York City to Los Angeles (network elements 501 and 504, respectively) is presently required, and the link will be composed, in series, of W1 coupling port 511 of element 501 to port 513 in network element 502; W1 coupling port 514 of element 502 to port 515 of element 503; and W2 coupling port 516 of element 503 to port 517 of element 504. Then, input packet 520 incoming to network element 501 (New York City) and having a destination of network element 504 (Los Angeles) is immediately routed over this established link. At network element 504, the propagated packet is delivered as output packet 521 via client interface port 518.

In a similar manner, a dedicated path between elements 506 and 507 (St. Louis and Minneapolis, respectively) is shown as established using W2 between network elements 506 and 502, and W3 between elements 502 and 507.

Links generated in this manner—as based upon the global routing tables—are characterized by their rigidity, that is, it takes several seconds for NC&M 220 to determine the connections to establish the links, to download the connectivity information for the links, and establish the input and output ports for each network element. Each link has characteristics of a circuit-switched connection, that is, it is basically a permanent connection or a dedicated path or “pipe” for long intervals, and only NC&M 220 can tear down and re-establish a link in normal operation. The benefit of such a dedicated path is that traffic having an origin and a destination which maps into an already-established dedicated path can be immediately routed without the need for any set-up. On the other hand, the dedicated path can be, and

most often is, inefficient in the sense that the dedicated path may be only used a small percentage of the time (e.g., 20%-50% over the set-up period). Moreover, switching device 430 (see FIG. 4) embedded in each network element which interconnects input and output ports has only a finite number of input/output ports. If the above scenario is changed so that link from St. Louis to Minneapolis is required and a port already assigned to the New York to Los Angeles link is to be used (e.g., port 514 of network element 502), then there is a time delay until NC&M 220 can respond and alter the global routing tables accordingly.

Now the example is expanded so that the subject matter in accordance with the principles of the present invention is overlaid on the above description. First, a parameter called the "label-switched state" is introduced and its use in routing is discussed; then, in the next paragraph, the manner of generating the label-switch state is elucidated. The label-switch state engenders optical label switching.

NC&M 220 is further arranged so that it may assign the label-switch state to each packet incoming to a network element from a client interface—the label-switch state is appended by Plug & Play module 132 and, for the purposes of the present discussion, the label-switch state is commensurate with header 210 (see FIG. 2). The label-switch state is computed by NC&M 220 and downloaded to each network element 501-507 in the form of a local routing table. With reference to FIG. 6, there is shown network element 501 and its embedded switch 601 in pictorial form. Also shown is incoming optical fiber 602, with delay loop 603, carrying packet 620 composed of header 210 and payload 211—payload 211 in this case is packet 520 from FIG. 5. Fiber 6022 delivers a delayed version of packet 620 to network element 501. Also, a portion of the light energy appearing on fiber 602 is tapped via fiber 6021 and inputted to optical module 410 which processes the incoming packet 620 to detect header 210—header 210 for packet 620 is shown as being composed of the label-switch state '11101011000', identified by reference numeral 615. Also shown in FIG. 6 is local look-up table 610, being composed of two columns, namely, "Label-switch State" (column 611), and "Local Address" (column 612). The particular label-switch state for packet 620 is cross-referenced in look-up table 610 to determine the routing of the incoming packet. In this case, the label-switch state for packet 620 is the entry in the fourth row of look-up table 610. The local switch address corresponding to this label-switch state is "0111", which is interpreted as follows: the first two binary digits indicate the incoming port, and the second two binary digits indicate the output port. In this case, for the exemplary four-input, four-output switch, the incoming packet is to be routed from input port "01" to output port "11", so switch 601 is switched accordingly (as shown). After the delay provided by fiber delay 603, the incoming packet on fiber 6022 is propagated onto fiber 604 via switch 601.

The foregoing description of label-switch state indicates how it is used. The manner of generating the label-switch state is now considered. NC&M 220, again on a periodic basis, compiles a set of local look-up tables for routing/switching the packet through each corresponding network element (such as table 610 for network element 501), and each look-up table is then downloaded to the corresponding network element. The generation of each look-up table takes into account NC&M 220's global knowledge of the network 500. For instance, if incoming packet 620 to network 501 is destined for network 504 (again, New York to Los Angeles), if port 510 is associated with incoming port "01" and serves fiber 602, and if outgoing port 511 is associated with

outgoing port "11" and serves fiber 604, then NC&M 220 is able to generate the appropriate entry in look-up table 610 (namely, the fourth row) and download table 610 to network element 510. Now, when packet 520 is processed by electro-optical module 132 so as to add header 210 to packet 520 to create augmented packet 620, NC&M 220's knowledge of the downloaded local routing tables as well as the knowledge of the destination address embedded in packet 520 as obtained via module 132 enables NC&M 220 to instruct module 132 to add the appropriate label-switch state as header 210—in this case '11101011000'.

It can be readily appreciated that processing a packet using the label-switch state parameter is bursty in nature, that is, after switch 601 is set-up to handle the incoming label-switch state, switch 601 may be returned to its state prior to processing the flow state. For example, switch 601 may have interconnected input port '01' to output port '10' prior to the arrival of packet 620, and it may be returned to the '0110' state after processing (as determined, for example, by a packet trailer). Of course, it may be that the circuit-switched path is identical to the label-switch state path, in which case there is no need to even modify the local route through switch 601 for processing the label-switch state. However, if it is necessary to temporarily alter switch 601, the underlying circuit-switched traffic, if any, can be re-routed or re-sent.

As discussed so far, label switching allows destination oriented routing of packets without a need for the network elements to examine the entire data packets. New signaling information—the label—is added in the form of optical signal header 210 which is carried in-band within each wavelength in the multi-wavelength transport environment. This label switching normally occurs on a packet-by-packet basis. Typically, however, a large number of packets will be sequentially transported towards the same destination. This is especially true for bursty data where a large block of data is segmented in many packets for transport. In such cases, it is inefficient for each particular network element to carefully examine each label and decide on the routing path. Rather, it is more effective to set up a "virtual circuit" from the source to the destination. Header 210 of each packet will only inform continuation or ending of the virtual circuit, referred to as a flow state connection. Such an end-to-end flow state path is established, and the plug-and-play modules in the network elements will not disrupt such flow state connections until disconnection is needed. The disconnection will take place if such a sequence of packets have come to an end or another packet of much higher priority requests disruption of this flow state connection.

The priority aspect of the present invention is also shown with respect to FIG. 6. The local look-up table has a "priority level" (column 613) which sets forth the priority assigned to the label-switching state. Also, header 210 has appended priority data shown as the number '2' (reference numeral 616). Both the fourth and fifth row in the "label-switch state" column 611 of table 610 have a local address of '0111.' If an earlier data packet used the entry in the fifth row to establish, for example, a virtual circuit or flow switching state, and the now another packet is processed as per the fourth row of column 611, the higher priority data ('2' versus '4', with '1' being the highest) has precedent, and the virtual circuit would be terminated.

Detailed Illustrative Embodiments

In order to achieve ultra-low latency IP over WDM label switching, processing of the optical header at each optical

switch must be kept to a minimum during the actual transmission of the optical packet. To achieve this end, a new signaling architecture and packet transmission protocol for performing optical WDM label switching is introduced.

The signaling and packet transmission protocols decouple the slow and complex IP routing functions from the ultra-fast WDM switching and forwarding functions. This decoupling is achieved via the setup of an end-to-end routing path which needs to be performed very infrequently. To send IP packets from a source to a destination, the following step is executed in accordance with the present invention: optical packet transmission, where the arrival of the optical packet triggers the local header processing which among other things looks up the output port for forwarding the packet on to the next hop based on the optical label inside the optical header.

Although routing path setup involves invoking the routing function which is generally a slow and complicated procedure, it is performed prior to packet transmission handling, and hence it is not in the critical path that determines transmission latency.

Routing Path Setup

During routing path setup, the internal connection table of a WDM packet switch will be augmented with a label-switch look-up table, and contains the pertinent packet forwarding information. In particular, in the interest of achieving ultra-low latency and hardware simplicity, the inventive scheme produces label-switch states that remain constant along the flow path. For example, label-switch assignments include the following techniques:

- (1) Destination-based flow label assignment—In this scheme the destination, e.g. a suitable destination IP address prefix can be used as the label-switch state in next hop look-up. In addition to having no need to modify the optical header, the same header can be used in the event of deflection routing.
- (2) Route-based flow label assignment—In this scheme the label-switch state assigned refers to the end-to-end route that is computed dynamically at the label-switch state setup phase. The advantage of this scheme is that it can be specialized to meet the Quality-of-Service requirements for each individual label-switched states.

Switching Conflict Resolution

The present-day lack of a viable optical buffer technology implies that conventional buffering techniques cannot be used to handle switching conflicts. As previously described, the invention embodiment utilizes fixed delay implemented by an optical fiber to allow switching to occur during this time delay, but not to achieve contention resolution as electrical buffers do in conventional IP routers. To resolve switching contentions, in accordance with the present invention, the following three methods are used:

- (a) Limited wavelength interchange—where a packet is routed through the same path but at a different wavelength. Since this wavelength conversion is utilized just to avoid the contention, it is not necessary that the network elements must possess the capability of converting to any of the entire wavelength channels. Rather, it is sufficient if they can convert some of the entire wavelength channels. This wavelength conversion converts both the signaling header and the data payload. Care must be taken to prevent a packet from undergoing too many wavelength conversions which will result in poor signal fidelity. A possible policy is to allow only one conversion, which and can easily be enforced by encoding the original wavelength in the

optical header. This way an intermediate WDM switch will allow conversion if and only if it is carried on its original wavelength.

- (b) Limited deflection routing—where a packet may be deflected to a neighboring switching node from which it can be forwarded towards its destination. Care again must be taken to prevent a packet from being repeatedly deflected, thereby causing signal degradation, as well as wasting network bandwidth. A solution scheme is to record a "timestamp" field in the optical header, and allow deflections to proceed if and only if the recorded timestamp is no older than a maximum limit.

- (c) Prioritized packet preemption—where a newly arrived packet may preempt a currently transmitting packet if the arriving packet has a higher priority. The objective is to guarantee fairness to all packets so that eventually a retransmitted packet can be guaranteed delivery. In this scheme, each packet again has a timestamp field recorded in its optical header, and older packets have higher priority compared to newer packets. Furthermore a retransmitted packet assumes the timestamp of the original packet. This way, as a packet "ages," it increases in priority, and will eventually be able to preempt its way towards its destination if necessary.

It is noted that in all these schemes the optical header can remain constant as it moves around in the network. This is consistent with the desire to keep the optical switching hardware fast and simple. It is also possible to consider combinations of these schemes.

Routing Protocol

For a network the size of the NGI, centralized routing decisions are quite unfeasible, so the approach needs to be generalized to distributed decision making. Hierarchical addressing and routing are used as in the case of IP routing. When a new connection is requested, NC&M 220 decides whether a WDM path is provisioned for this (source, destination) pair within the WDM-based network. If it is, the packets are immediately sent out on that (one-hop IP-level) path. If no such path is provisioned, NC&M 220 decides on an initial outbound link for the first WDM network element and a wavelength to carry the new traffic. This decision is based on the rest of the connections in the network at the time the new connection was requested. NC&M 220 then uses signaling, through an appropriate protocol, to transfer the relevant information to the initial WDM network element to be placed in the signaling header. After the initial outbound link is determined, the rest of the routing decisions are taken at the individual NE's according to the optical signaling header information. This method ensures that the routing tables at each switching node and the signaling header processing requirements are kept relatively small. It also enables the network to scale easily in terms of switching nodes and network users. It is noted, too, that multiple WDM subnetworks can be interconnected together and each sub-network will have its own NC&M.

When a path is decided upon, within a WDM NE, the optical switches can be set in that state (i) for the duration of each packet through the node and then revert back to the default state (called optical label-switching), or (ii) for a finite, small amount of time (called flow switching). The former case performs routing on a regular packet-by-packet basis. The system resources are dedicated only when there is information to be sent and at the conclusion of the packet, these resources are available for assignment to another packet. The latter case is used for large volume bursty mode traffic. In this case, the WDM NE only has to read a flow state label from the optical signaling header of subsequent

packets arriving at the NE to be sure such packet is bound for the same destination, without the need to switch the switching device, and forward the payload through the already existing connection through the NE as previously established by the optical label-switching.

The packets are self-routed through the network using the information in the signaling header of each packet. When a packet arrives at a switching node, the signaling header is read and either the packet is forwarded immediately through an already existing flow state connection or a new appropriate outbound port is chosen according to the routing table. Routing tables in each node exist for each wavelength. If the packet cannot follow the selected outbound port because of contention with another packet (the selected outbound fiber is not free), the routing scheme will try to allocate a different wavelength for the same outbound port (and consequently the signal will undergo wavelength translation within the switching node). If no other eligible wavelength can be used for the chosen outbound port, a different outbound port may be chosen from another table, which lists secondary (in terms of preference) outbound links.

This routing protocol of the inventive technique is similar to the deflection routing scheme (recall the Background Section), where the session is deflected to some other outbound link (in terms of preference) if the preferred path cannot be followed. The packet is not allowed to be continuously deflected. In traditional routing protocols, a hop count is used to block a session after a specified number of hops. In the new scheme, in case no header regeneration is allowed at the switching nodes, then the hop count technique cannot be used. Alternatively, the optical signaling header characteristics (i.e., the signaling header's SNR) can be looked upon to decide whether a packet should be dropped. IP Routing Algorithm in WDM Layer

The technique used by NC&M 220 to determine the routing tables is based upon shortest path algorithms that route the packets from source to destination over the path of least cost. Specific cost criteria on each route, such as length, capacity utilization, hop count, or average packet delay can be used for different networks. The objective of the routing function is to have good performance (for example in terms of low average delay through the network) while maintaining high throughput. Minimum cost spanning trees are generated having a different node as a root at each time, and the information obtained by these trees can then be used to set-up the routing tables at each switching node. If deflection routing as outlined above is implemented, the k-shortest path approach can be used to exploit the multiplicity of potential routing paths. This technique finds more than one shortest path, with the paths ranked in order of cost. This information can be inputted into the switching node routing tables, so that the outbound link corresponding to the minimum cost path is considered first, and the links corresponding to larger cost paths are inputted in secondary routing tables that are used to implement deflection routing. Description of Plug-and-Play Modules

The present invention is based upon two types of Plug-and-Play modules to be attached to the WDM network elements. Introduction of these Plug-and-Play modules add optical label switching capability to the existing circuit-switched network elements.

In FIG. 3, both header encoder 321 and header remover 322 were shown in high-level block diagram form; FIGS. 7 and 8 show, respectively, a more detailed schematic for both encoder 321 and remover 322.

In FIG. 7, IP packets or datagrams are processed in microprocessor 710 which generates each optical signaling

header 210 for label switching. Optical signaling header 210 and the original IP packet 211 are emitted from microprocessor 710 at baseband. Signaling header 210 is mixed in RF mixer 720 utilizing local oscillator 730. Both the mixed header from mixer 720 and the original packet 211 are combined in combiner 740 and, in turn, the output of combiner 740 is encoded to an optical wavelength channel via optical modulator 760 having laser 750 as a source of modulation.

In FIG. 8, the optical channel dropping out of a network element is detected by photodetector 810 and is electrically amplified by amplifier 820. Normally, both photodetector 810 and the amplifier 820 have a frequency response covering only the data payload but not the optical signaling header RF carrier frequency provided by local oscillator 730. Low-pass-filter 830 further filters out any residual RF carriers. The output of filter 830 is essentially the original IP packet sent out by the originating IP router from the originating network element which has been transported through the network and is received by another IP router at another network element.

Block diagram 900 of FIG. 9 depicts the elements for the detection process effected by Plug-and-Play module 410 of FIG. 4 to convert optical signal 901, which carries both label-switching signaling header 210 and the data payload 211, into baseband electrical signaling header 902. Initially, optical signal 901 is detected by photodetector 910; the output of photodetector 910 is amplified by amplifier 920 and filtered by high-pass filter 930 to retain only the high frequency components which carry optical signaling header 210. RF splitter 940 provides a signal to local oscillator 950, which includes feedback locking. The signal from local oscillator 950 and the signal from splitter 940 are mixed in mixer 960, that is, the high frequency carrier is subtracted from the output of filter 920 to leave only the information on label-switching signaling header 210. In this process, local oscillator 950 with feedback locking is utilized to produce the local oscillation with the exact frequency, phase, and amplitude, so that the high frequency component is nulled during the mixing of this local oscillator signal and the label-switching signaling header with a high-frequency carrier. Low-pass filter 970, which is coupled to the output of mixer 960, delivers baseband signaling header 210 as electrical output signal 902.

The circuit diagram of FIG. 10 shows an example of a more detailed embodiment of FIG. 4. In FIG. 10, each header detector 1010, 1020, . . . , 1030, . . . , or 1040 processes information from each wavelength composing the optical inputs arriving on paths 1001, 1002, 1003, and 1004 as processed by demultiplexers 1005, 1006, 1007, and 1008, respectively; each demultiplexer is exemplified by the circuit 900 of FIG. 9. The processed information is grouped for each wavelength. Thus, for example, fast memory 1021 receives as inputs, for a given wavelength, the signals appearing on lead 1011 from header detector 1010, . . . , and lead 1034 from header detector 1030. Each fast memory 1021-1024, such as a content-addressable memory, serves as an input to a corresponding label switch controller 1031-1034. Each label switch controller 1031-1034 also receives circuit-switched control signals from network element switch controller 420 of FIG. 4. Each label switch controller intelligently chooses between the circuit switched control as provided by controller 420 and the label switched information supplied by its corresponding fast memory to provide appropriate control signals the switching device 430 of FIG. 4.

Flow diagram 1100 of FIG. 11 is representative of the processing effected by each label-switch controller

1031–1034. Using label-switch controller 1031 as exemplary, inputs from circuit-switched controller 420 and inputs from fast memory 1021 are monitored, as carried out by processing block 1110. If no inputs are received from fast memory 1021, then incoming packets are circuit-switched via circuit-switched controller 420. Decision block 1120 is used to determine if there are any inputs from fast memory 1021. If there are inputs, then processing block 1130 is invoked so that label-switch controller 1031 can determine from the fast memory inputs the required state of switching device 430. Then processing block 1160 is invoked to transmit control signals from label-switch controller 1031 to control switching device 430. If there are no fast memory inputs, then the decision block 1140 is invoked to determine if there are any inputs from circuit-switched controller 1140. If there are inputs from circuit-switched controller 420, then processing by block 1150 is carried out so that label-switch controller 1031 determines from the inputs of circuit-switched controller 420 the required state of switching device 430. Processing block 1160 is again invoked by the results of processing block 1150. If there are no present inputs from circuit-switched controller 1140 or upon completion of processing block 1160, control is returned to processing block 1110.

By way of reiteration, optical label-switching flexibly handles all types of traffic: high volume burst, low volume burst, and circuit switched traffic. This occurs by interworking of two-layer protocols of the label-switched network control. Thus, the distributed switching control rapidly senses signaling headers and routes packets to appropriate destinations. When a long stream of packets reach the network element with the same destination, the distributed switching control establishes a flow switching connection and the entire stream of the packets are forwarded through the newly established connections.

A label switching method scales gracefully with the number of wavelengths and the number of nodes. This results from the fact that the distributed nodes process multi-wavelength signaling information in parallel and that these nodes incorporate predicted switching delay in the form of fiber delay line. Moreover, the label switching utilizes path deflection and wavelength conversion for contention resolution.

Optical Header Processing

The foregoing description focused on optical header processing at a level commensurate with the description of the overall NGI system configured with the overlaid Plug-and-Play modules. Discussion of header processing at a more detailed level is now appropriate so as to exemplify how low-latency can be achieved at the circuit-detail level. To this end, the arrangement of FIG. 12, which is a more detailed block diagram encompassed by the earlier descriptions of FIGS. 9 and 10 especially, is considered. As seen in FIG. 12, optical signal 1001 serves as an input to demux 1005, both of which are re-drawn from FIG. 10. Furthermore, a detailed illustrative embodiment of header detector 1010 of FIG. 10 is now shown in FIG. 12. In particular, header detector 1010 includes in this embodiment: (a) dispersion compensator 1205 for correcting dispersion in the optical signal at optical wavelength λ_1 emanating from demux 1005; (b) optical-electrical converter 1210 (e.g., a photodetector) for producing electrical output signal 1211 from the optical signal departing compensator 1205; (c) a bank of local oscillators having frequencies f_1, f_2, \dots, f_N feeding multipliers 1221, 1231, \dots , 1241, respectively, for frequency-shifting the frequency components of electrical signal 1211 to intermediate frequencies

(IFs); (d) a bank of IF band-pass-filters (IF-BPF) 1222, 1232, \dots , 1242 responsive to multipliers 1221, 1231, \dots , 1241, respectively, to filter the frequency domain energy in header signals 1213, \dots , 1215 shown at the top left-hand of FIG. 12; (e) a cascade of envelope detector/decision circuit pairs 1223/1224, 1233/1234, \dots , 1243/1244 wherein the presence of frequency domain energy in any of the frequency bands centered at f_1, f_2, \dots, f_N is denoted as a logic '1' at the output of the decision circuits 1224, 1234, \dots , 1244, whereas the absence of frequency domain energy at f_1, f_2, \dots, f_N is denoted as a logic '0'; (f) logic circuit 1250 which provides a switch selection signal on selection lead 1260, the function of which being discussed in more detail in the operational description below; (g) delay circuits 1225, 1235, \dots , 1245 coupled to the BPF filters 1222, \dots , 1242; (h) switches 1261, 1262, \dots , 1263, coupled to delay circuits 1225, \dots , 1245 as inputs, and being controlled by the signal on lead 1260; (i) input lead 1265, connected to switches 1261, \dots , 1263, which serves as an input to demodulator 1291; (j) detector 1292 responsive to demodulator 1291; and (k) read circuit 1293 which outputs signal 1011 of FIG. 10.

The operation of header detector 1010 of FIG. 12 is as follows. It is assumed that the second type of 'Plug-and-Play' module of FIG. 4 injects a 2.5 Gbps IP data packet (e.g., with QPSK/QAM modulation) which is sub-carrier multiplexed with a 155 Mbps header packet (e.g., with QAM modulation) at a center frequency f_1 ; as before, the header precedes the data payload in time and both are both carried by the optical wavelength λ_1 . In each network node which receives the combined header and payload at wavelength λ_1 , the sub-carrier header at f_1 is detected by envelope detector 1212. Because there is energy present in the frequency band centered at f_1 due to the existence of the header signal, decision circuit 1224 detects a logic '1', whereas all other decision circuits detect a logic '0'. This combination of logic signals ('100...0') in parallel at the input to logic circuit 1250 generates the selection signal 1260 which effects the closure of only switch 1261. (It is important to emphasize that the input logic signals are generated concurrently and in parallel, rather than in series, thereby significantly speeding up the header detection process.) The actual header signal provided at the output of IF-BPF 1222 serves, after the delay imposed by delay circuit 1225, as the input to demodulator 1291 via lead 1265. The delay of circuit 1225 is not critical, other than the delay is greater than the time required to derive the logic signal via envelope detector 1223 and decision circuit 1224, plus the time required to compute the control signal on selection signal lead 1260 in logic circuit 1250 and to close switch 1261. (The delay can be implemented digitally, e.g., by replacing each analog delay in FIG. 12 by a cascade of a demodulator and a digital delay.) Therefore, the header signal at f_1 is the only header signal that will be demodulated by demodulator 1291 (e.g., a QAM demodulator), and the demodulated baseband data burst is then detected by detector 1292 (e.g., a 155 Mbps burst-mode receiver), and read by circuit 1293 (e.g., a microprocessor).

This foregoing operational description has focused only on the detection of the optical header to control the routing path through switching device 430 of FIG. 4. As alluded to in the Background Section, header replacement is now considered important to present-day NGI technology so as to accomplish high-throughput operation in a packet switched network in which data paths change due to, for example, link outages and variable traffic patterns. Moreover, header replacement is useful to maintain protocol compatibility. The components of FIG. 12 which have heretofore not been

described play a central role in header replacement. Actually, the notion of header replacement has a broader connotation in that the header may be composed of various fields, such as a "label" field and a "time-to-leave" field. The description to this point has used the header and label interchangeably; however, it is now clear that the header may actually have a plurality of fields, and as such any or all may be replaced at any node.

Now continuing with the description of FIG. 12, it is shown that logic circuit 1250 also provides a second selection signal on selection lead 1270; this lead control switches 1271, 1272, . . . , 1273 which are all connected to lead 1295. Interposed between lead 1295 and header output lead 1011 is write circuit 1294 in cascade with modulator 1296. Write circuit 1294 is responsible for providing a new header signal. The header signal that arrives at the input to demux 1005 is referred to as the active header signal—in the first node to process the header signal, the active header signal and the original header signal coalesce. The new header signal, rather than actually overwriting the active header signal, is placed in a frequency band above the frequency band of the active header signal, that is, the next highest available center frequency from the set f_1, f_2, \dots, f_N is utilized to propagate the new header signal. To select the next highest available center frequency, logic circuit 1250 is arranged so that if decision circuits 1224, 1234, . . . , 1244 yield an active center frequency f_i , then selection signal 1270 will close only the switch from the set 1271, 1272, . . . , 1273 which connects lead 1295 to center frequency f_{i+1} . That is, lead 1295 will be connected to the multiplier from the set 1281, 1282, . . . , 1283 which corresponds to frequency f_{i+1} . The outputs of multipliers 1281, 1282, . . . , 1283 are connected to lead 1284, which serves as a second input to optical switch/add-drop multiplexer 1207; the other input is provided by the header signal on lead 1011. Circuit 1207 now has a dual functionality, namely, it operates as switching device 430 of FIG. 4, but is also arranged to convert an input electrical signal, such as on lead 1284, to an optical signal for propagation by the same optical wavelength present at the input to circuit 1207 (in this case, wavelength λ_1). Accordingly, the new header signal on lead 1284 is frequency shifted above the data payload as well as all other existing headers arriving on lead 1208; this is shown in frequency domain visualization in the top right-hand corner of FIG. 12, which is counterpart of the visualization in the top left-hand corner. So that the new header signal is placed ahead of the data payload in time, delay is introduced by fiber loop 1206.

The operation of the arrangement of FIG. 12 for header replacement is as follows. Again, the same example is used so that an optical header plus a data payload is incoming to the network node immediately following the node that injected the packet. It is desired to write a new header signal, and in the embodiment of FIG. 12, the output of read circuit 1293 serves as an input to write circuit 1294; in this manner, the active header signal may serve as an aid in computing the new header signal. The new header signal is conveyed by center frequency f_2 since the incoming active header signal is centered about f_1 . In effect, the new header signal is written on the original light which contains both the data packet and the old sub-carrier header or active header signal at f_1 . Therefore, the modulated light which leaves the given node contains the data packet and two sub-carrier header signals. (Two illustrative writing techniques, both of which use a high-speed (~10 GHz) LiNbO₃-based modulator/switch, will be explained later.) The carrier frequency f_2 is higher than f_1 by about 200 MHz for the 155 Mbps data, but

the frequency difference between f_1 and f_2 can be smaller if a more spectral efficient modulation method such as M-QAM is adopted. Note that this node has the intelligence via logic circuit 1250 to know that the active header signal uses sub-carrier f_1 and the new header signal is written onto sub-carrier f_2 .

In a similar manner, the third network node along the route will read the active header signal on sub-carrier f_2 and write a new header information onto sub-carrier f_3 , and the process continues until the modulation bandwidth of optical switch/ADM 1207 is exhausted. For example, a typical 10 GHz external LiNbO₃-based modulator/switch can write about 40 $((10-2)/0.2)$ new sub-carrier headers signals, where it has been assumed that the 2.5 Gbps data occupies a bandwidth of 2 GHz.

FIG. 12 actually illustrates the implementation details of the fourth network node along the route over which a packet travels. The three sub-carrier headers on λ_1 are simultaneously down-converted to IF band, and due to their existence, decision circuits 1224, 1234, . . . , 1244 generate a logic '1' signal to logic circuit 1250 in the pattern "111000 . . . 000". Note that if there are 40 down-converters in this example, 37 decision circuits will generate logic '0's because there are no sub-carriers on f_4, f_5, \dots, f_{40} . Logic circuit 1250 uses the output "1110000 . . . 0" (three ones and thirty-seven zeros) to control the 40 microwave switches 1261, 1262, . . . , 1263 such that only the third microwave switch is closed and all other 39 switches are open. Therefore, the header information on f_3 becomes the active header signal that is then demodulated by demodulator 1291. Immediately after the "read" process, the new header signal is generated by write circuit 1294 and then applied to modulator 1296 at IF. As depicted in FIG. 12, the new header signal is launched to the fourth microwave switch which is turned on by selection signal 1270. The new header signal is then up-converted by f_4 , and is used to modulate the delayed main-path signal on optical path 1208 (which originally contains only three sub-carrier headers). The resultant modulated light therefore contains four sub-carrier headers as depicted.

It is noted that, in terms of presently available components, the processing time of the envelope detectors (1223 . . .), the decision circuits (1224, . . .), the logic circuit (1250), and the turning-on of a particular microwave switch (1261, . . .) should take less than 30 ns. On the other hand, if it is assumed that there are 15 bits in each packet header signal, then the time to read 15 bits, write 15 bits, and add 10 preamble bits can take about 260 ns for a 155 Mbps burst. Therefore, allowing for some variations, each header signal is about 300 ns. This means that the length of delay line 1206 in main optical path 1208 should be around 60 meters.

There exist some upper bounds on the proposed sub-carrier header insertion technique of FIG. 12: (a) the sub-carriers at carrier frequencies as high as 10 is GHz can become severely attenuated due to fiber dispersion after a certain transmission distance (usually tens of kilometers). Fortunately, this problem can be solved by repeatedly using dispersion compensation fibers (such as compensator 1205) or chirped fiber gratings at every network node; (b) at each intermediate network node, its modulator 1296 (e.g., a LiNbO₃-based modulator) modulates the incoming "modulated" light by a new sub-carrier header signal, and this can cause new intermodulation distortion products. However, the present technology is such that the nonlinear distortion penalty after 40 times of writing consecutive sub-carrier header signals is not large enough to degrade the bit-error-ratio (BER) of both the data payload and the subcarrier

header signal up to a distance of 2000 km; and (c) since the maximum number of insertable sub-carrier header signals are about 40 using a 10 GHz modulator, at some point in the network the entire sub-carrier header signals will have to be erased so that a new set of sub-carrier header signals can be written onto the received light all over again. Being conservative, it is determined that the maximum transmission distance using the arrangement of FIG. 12 is about 2000 km. Therefore, it is feasible that several "reset" network nodes are implemented, configured as shown in FIG. 13, which are sparsely located across the nation, to guarantee that the 40 times-writing limit is never exceeded. It is noted, however, that not every node will insert a new header signal (recall the new header signal is typically inserted due to slowly varying network outages or for protocol compatibility). If this is indeed the case, then it is anticipated that 40 header signal insertions are more than enough to cover any cross-nation transport of an optical packet.

However, to be sure that a new header signal can be inserted when needed, preferably some or even all of the network nodes are arranged with the circuitry 1300 of FIG. 13. The primary difference between FIGS. 12 and 13 is in the upper path of FIG. 12 wherein the main-path optical signal appearing at the output of compensator 1205 is converted back to electrical domain via opto-electrical converter 1210, with all of its old sub-carrier header signals being erased by using low-pass filter (LPF) 1311. A new, single sub-carrier header signal centered at frequency f_h is added to the regenerated data payload in electrical adder 1313; the data payload is regenerated in the conventional electrical manner by timing recovery-and-decision circuitry 1312. Together the data payload and new header signal modulate electrical-optical transmitter 1314 having the same wavelength λ_1 . Therefore, from this reset node on, another 40 sub-carrier header signals can be written before there is the (unlikely) need to reset again.

Another Illustrative Embodiment of a Header Insertion Technique

The circuit arrangements of FIGS. 12 and 13 were realized without the need for local light injection. In order to increase the transmission distance beyond the anticipated 2000 km limit, another node header processing arrangement is required, as now depicted in FIG. 14; this arrangement deploys the injection of local light at wavelength λ_1 . The main difference between FIGS. 12 and FIG. 14 is shown the processing path composed of the following components: (a) opto-electrical converter 1410; (b) decision circuit 1440 responsive to converter 1410; (c) the series arrangement of delay line 1411 and optical gate 1420, with delay line 1411 being responsive to the output of compensator 1205; (d) coupler 1430 responsive to gate 1420; (e) light feedback path 1431 for feeding output light from coupler 1430 to its input, path 1431 being composed of erbium-doped fiber amplifier (EDFA) 1432 and optical switch 1433; (f) light modulator 1450 responsive to the electrical signal appearing on path 1284, as before; and (g) optical adder 1460 responsive to both light modulator 1450 and optical switch/ADM 1207. An augmented optical packet 1470, with the form shown in the lower left corner of FIG. 14, now arrives at the network node of FIG. 14 via optical path 1001. Preamble 1471 in optical packet header 1470, after optical-to-electrical conversion in opto-electrical converter 1410, directs detection circuit 1440 to turn on optical gate 1420 and let short CW light burst 1472 (about 30 ns in duration) at λ_1 pass through to coupler 1430. CW light burst 1472 then loops several times via feedback path 1431 to lengthen the

CW light duration to about 300 ns; this extended duration CW burst serves as an input to light modulator 1450 via output path 1451 from coupler 1430. The new sub-carrier header signal appearing on lead 1284 then modulates this locally regenerated CW light burst on lead 1452 via light modulator 1450 (e.g., via a LiNbO₃ modulator). The modulated light which appears on output lead 1452 of light modulator 1450, containing only the new, active sub-carrier header signal, is then combined in optical adder 1460 along with the main-path light which contains the data payload and the old sub-carrier header signals as emitted by switch 1207. The time of occurrence of the new sub-carrier header signal arrives essentially concurrently with original optical packet 1470 at optical adder 1460. (In an intermediate network node, it is important for the node to re-modulate the new header onto the original wavelength in the same time frame as the payload data.) Thus the light pulse conveying the new active header signal occupies the same time interval as the incoming header signals 1473, with the difference being that the old header signals and the new active header signal are separated in the frequency domain by their corresponding sub-carrier frequencies. That is, each time a new header signal is added, the light conveying the new header signal at the given wavelength λ_1 is overlaid on the incoming light signal conveying the old header signals, but being such that the frequency domain characteristics are determined by the sub-carrier frequencies.

With this technique, no additional nonlinear distortions are generated due to the modulation of an already modulated light. As long as the optical power ratio between the main-path light from switch 1207 and the locally-injected light from light modulator 1450 is optimized, and the modulation depths of the sub-carrier headers and data payload are optimized, transmission can be beyond 2000 km is effected.

An Alternative Header Replacement Technique

It is also possible to use an optical notch filter which has a very high finesse to notch out the old sub-carrier header signal. The network node configuration 1500 is shown in FIG. 15; it is readily appreciated that node configuration 1500 is greatly simplified relative to the implementation of FIG. 12. The sub-carrier header signal at centered at f_h is purposely allocated at high-frequency carrier (e.g., 9 GHz) so that the header signal conveyed f_h will not affect the data payload in the low frequency region. The output of compensator 1205 feeds optical circulator 1510, which is coupled to fiber Fabry-Perot (FFP) notch filter 1515 and attenuator 1520 in series. The combined effect of these components is to notch out the header signal centered at f_h ; the spectrum of the input to optical circulator 1510 is shown in the top left corner, whereas the spectrum of the output of circulator 1510 is shown in the top center. The newly inserted header signal is provided by the series combination: write circuit 1294; modulator 1296; up-converter 1281 being driven by sub-carrier f_h , in a much simplified manner as that of FIG. 12.

Optical Technology

Optical technologies span a number of important aspects realizing the present invention. These include optical header technology, optical multiplexing technology, optical switching technology, and wavelength conversion technology.

(a) Optical Header Technology

Optical header technology includes optical header encoding and optical header removal as discussed with respect to FIGS. 3 and 4. In effect, optical header 210 serves as a signaling messenger to the network elements informing the network elements of the destination, the source, and the length of the packet. Header 210 is displaced in time

compared to the actual data payload. This allows the data payload to have any data rates/protocols or formats.

(b) Optical Multiplexing Technology

Optical multiplexing may illustratively be implemented using the known silica arrayed waveguide grating structure. This waveguide grating structure has a number of unique advantages including: low cost, scalability, low loss, uniformity, and compactness.

(c) Optical Switching Technology

Fast optical switches are essential to achieving packet routing without requiring excessively long fiber delay as a buffer.

Micromachined Electro Mechanical Switches offer the best combination of the desirable characteristics: scalability, low loss, polarization insensitivity, fast switching, and robust operation. Recently reported result on the MEM based Optical Add-Drop Switch achieved 9 microsecond switching time

(d) Wavelength Conversion Technology

Wavelength conversion resolves packet contention without requiring path deflection or packet buffering. Both path deflection and packet buffering cast the danger of skewing the sequences of a series of packets. In addition, the packet buffering is limited in duration as well as in capacity, and often requires non-transparent methods. Wavelength conversion, on the other hand, resolves the blocking by transmitting at an alternate wavelength through the same path, resulting in the identical delay. Illustratively, a WSXC with a limited wavelength conversion capability is deployed.

Although various embodiments which incorporate the teachings of the present invention have been shown and described in detail herein, those skilled in the art can readily devise many other varied embodiments that still incorporate these teachings.

What is claimed is:

1. A method for propagating a data payload from an input network element to an output network element in a wavelength division multiplexing (WDM) network composed of a plurality of network elements, the data payload having a given format and protocol, the method comprising the steps of

generating and storing a local routing look-up table in each of the network elements, each local routing table determining alternative local routes through the associated one of the network elements,

adding a header to the data payload prior to inputting the data payload to the input network element to produce an optical signal, the header having a format and protocol and being indicative of a local route through each of the network elements for the data payload and the header, the format and protocol of the data payload being independent of the format and protocol of the header,

detecting the header at the network elements to produce a switch control signal as the data payload and header propagate through the WDM network,

selecting one of the local routes for routing the optical signal through the network elements as determined by looking up the switch control signal in the corresponding local routing table, and

routing the optical signal through the network elements in correspondence to the selected route,

wherein the header is composed of a header signal being conveyed by a distinct carrier frequency such that the spectrum of the header signal occupies a frequency band above the data payload,

the step of detecting including the steps of
opto-electrically converting the optical signal to detect header information in the header signal, and
reading the header information to produce a switch control signal to route the incoming optical signal,
the method further comprising, prior to the step of routing, the steps of
optically processing the optical signal to delete the header signal and recover only the data payload, and
inserting a new header signal into the optical signal in place of the deleted header signal.

2. The method as recited in claim 1 wherein the step of converting includes the step of demodulating the header signal to produce a demodulated header signal.

3. The method as recited in claim 2 wherein the step of converting further includes the step, after the step of demodulating, of recovering the header information from the demodulated header signal.

4. The method as recited in claim 3 wherein the step of converting further includes the step, after the step of recovering, of reading the header information to produce the switch control signal to route the optical signal.

5. The method as recited in claim 4 wherein the step of reading includes the step of inputting the header information to a content-addressable memory to produce the switch control signal.

6. The method as recited in claim 1 wherein the step of inserting includes the step of modulating the new header signal using the carrier frequency.

7. The method as recited in claim 1 wherein the step of converting includes the step of down-converting the header signal to an intermediate frequency signal indicative of the header signal.

8. The method as recited in claim 7 wherein the step of down-converting includes the steps of locally generating the carrier frequency and multiplying the header signal by the local carrier frequency to produce the intermediate frequency signal.

9. The method as recited in claim 8 wherein the step of inserting includes the step of modulating the new header signal with the carrier frequency.

10. The method as recited in claim 9 further including an add-drop optical switch controlled by the switch control signal and wherein the step of inserting further includes the step of adding the modulated new header signal via the add-drop optical switch.

11. The method as recited in claim 10 wherein the step of inserting the new header signal includes the step of referencing the local routing table for routes through the optical switch.

12. The method as recited in claim 1 wherein the step of optically processing includes the steps of
circulating the optical signal in an optical circulator, and
passing the circulated optical signal through an optical notch filter with high finesse to remove the header signal.

13. A method for replacing a header and for routing an optical signal propagating at a given optical wavelength, the optical signal including both the header and a data payload, the header being composed of a header signal being conveyed by a distinct carrier frequency such that the spectrum of the header signal occupies a frequency band above the data payload, the method comprising the steps of

opto-electrically converting the optical signal to detect header information in the header signal,
reading the header information to produce a switch control signal to route the optical signal,

optically processing the optical signal to delete the header signal, and

inserting a new header signal into the optical signal in place of the deleted header signal.

14. The method as recited in claim 13 wherein the step of converting includes the step of demodulating the header signal to produce a demodulated header signal.

15. The method as recited in claim 14 wherein the step of converting further includes the step, after the step of demodulating, of recovering header information from the demodulated header signal.

16. The method as recited in claim 15 wherein the step of converting further includes the step, after the step of recovering, of reading the header information to produce the switch control signal to route the optical signal.

17. The method as recited in claim 16 wherein the step of reading includes the step of inputting the header information to a content-addressable memory to produce the switch control signal.

18. The method as recited in claim 13 wherein the step of inserting includes the step of modulating the new header signal using the carrier frequency.

19. The method as recited in claim 13 wherein the step of converting includes the step of down-converting the header signal to an intermediate frequency signal indicative of the header signal.

20. The method as recited in claim 19 wherein the step of down-converting includes the steps of locally generating the carrier frequency and multiplying the header signal by the local carrier frequency to produce the intermediate frequency signal.

21. The method as recited in claim 20 wherein the step of inserting includes the step of modulating the new header signal with the carrier frequency.

22. The method as recited in claim 21 further including an add-drop optical switch controlled by the switch control signal and wherein the step of inserting further includes the step of adding the modulated new header signal via the add-drop optical switch.

23. The method as recited in claim 22 wherein the step of inserting the new header signal includes the step of referencing the local routing table for routes through the optical switch.

24. The method as recited in claim 13 wherein the step of optically processing includes the steps of

circulating the optical signal in an optical circulator, and passing the circulated optical signal through an optical notch filter with high finesse to remove the header signal.

25. A method for replacing a header and for routing an optical signal propagating at a given optical wavelength, the optical signal including both the header and a data payload, the header being composed of a header signal being conveyed by a distinct carrier frequency such that the spectrum of the header signal occupies a frequency band above the data payload, the method comprising the steps of

opto-electrically converting the optical signal to obtain the header signal,

demodulating the header signal to produce a demodulated header signal,

detecting header information in the demodulated header signal,

reading the header information to produce a switch control signal to route the optical signal,

processing the optical signal to delete the header signal, determining a new header signal, and

inserting the new header signal into the optical signal in place of the deleted header signal.

26. A system for replacing a header and for routing an optical signal propagating at a given optical wavelength, the optical signal including both the header and a data payload, the header being composed of a header signal being conveyed by a distinct carrier frequency such that the spectrum of the header signal occupies a frequency band above the data payload, the system comprising

an opto-electrical converter, responsive to the optical signal, for converting the optical signal to detect header information in the header signal,

means, responsive to the converter, for reading the header information to produce a switch control signal to route the optical signal,

an optical processor, responsive to the optical signal, for deleting the header signal, and

means, coupled to the optical processor and the means for reading, for inserting a new header signal into the optical signal in place of the deleted header signal.

27. The system as recited in claim 26 wherein the converter includes a demodulator for demodulating the header signal to produce a demodulated header signal.

28. The system as recited in claim 27 wherein the converter further includes means, responsive to the demodulator, for recovering the header information from the demodulated header signal.

29. The system as recited in claim 28 wherein the converter further includes means, responsive to the means for recovering, for reading the header information to produce the switch control signal to route the optical signal.

30. The system as recited in claim 29 wherein means for reading includes means for inputting the header information to a content-addressable memory to produce the switch control signal.

31. The system as recited in claim 26 wherein means for inserting a modulator for modulating the new header signal using the carrier frequency.

32. The system as recited in claim 26 wherein the converter includes means for down-converting the header signal to an intermediate frequency signal indicative of the header signal.

33. The system as recited in claim 32 wherein means for down-converting includes a local generator for generating the carrier frequency and a multiplier for multiplying the header signal by the local carrier frequency to produce the intermediate frequency signal.

34. The system as recited in claim 33 wherein the means for inserting includes a modulator for modulating the new header signal with the carrier frequency.

35. The system as recited in claim 34 further including an add-drop optical switch controlled by the switch control signal and wherein means for inserting inputs the modulated new header signal into the add-drop optical switch.

36. The system as recited in claim 35 wherein the means for inserting the new header signal includes means for referencing the local routing table for routes through the optical switch.

37. The system as recited in claim 26 wherein the optical processor includes

an optical circulator for circulating the optical signal, and an optical notch filter with high finesse for filtering the circulated optical signal to remove the header signal.

38. A system for propagating a data payload from an input network element to an output network element in a wavelength division multiplexing (WDM) network composed of

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a plurality of network elements, the data payload having a given format and protocol, the system comprising

- a route generator for generating and storing a local routing look-up table in each of the network elements, each local routing table determining alternative local routes through the associated one of the network elements, 5
- an adder for adding a header to the data payload prior to inputting the data payload to the input network element to produce an optical signal, the header having a format and protocol and being indicative of a local route through each of the network elements for the data payload and the header, the format and protocol of the data payload being independent of the format and protocol of the header, 10
- a detector for detecting the header at the network elements to produce a switch control signal as the data payload and header propagate through the WDM network, 15
- a router for selecting one of the local routes for routing the optical signal through the network elements as determined by looking up the switch control signal in the corresponding local routing table, and 20

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- a switch for routing the optical signal through the network elements in correspondence to the selected route, wherein the header is composed of a header signal being conveyed by a distinct carrier frequency such that the spectrum of the header signal occupies a frequency band above the data payload,
- the detector further comprising
 - an opto-electrical converter for converting the optical signal to detect header information in the header signal, and
 - a reader for reading the header information to produce a switch control signal to route the incoming optical signal,
- the system further comprising
 - an optical processor, responsive to the optical signal, for processing the optical signal to delete the header signal and recover only the data payload, and
 - means, responsive to the optical processor, for inserting a new header signal into the optical signal in place of the deleted header signal.

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